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THE APPLICABILITY OF THE AZOTOBACTER (PLACQUE) METHOD FOR DETERMINING THE FERTILITY REQUIREMENTS OF ARIZONA SOILS[1]

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The soils of Arizona are characterized by extremely low nitrogen and organic matter contents, by relatively large amounts of total phosphorus and potassium, and by varying amounts of calcium carbonate. Practically all of the soils now under cultivation are calcareous—the quantities of $CaCO_3$ ranging from 2 to 20 per cent. During the past 4 years the author has analyzed approximately 4,000 soil samples which come from all parts of the state. Only two samples showed pH values lower than neutrality; the average was approximately pH 7.8.

Comparatively speaking, agriculture in Arizona is still in its infancy. Although Arizona ranks fifth among the 48 states in area (113,956 square miles) less than 1 per cent of this area is used at present for tilled agriculture. With the further development of water resources, the number of acres used for agricultural purposes will increase.

Few fertilizer experiments have been conducted. Field practices have shown that nitrogen fertilization is often helpful. It is generally assumed that the soil contains an abundance of potassium. This would be expected, since most of the soils are of granitic origin, and orthoclase feldspar would be the source of potassium. There is no evidence, to date, that Arizona soils need potash fertilizers.

Although these soils contain relatively large amounts of phosphorus, the amounts of available phosphorus are small, because of a rapid reversion to insoluble forms. This question of availability has been discussed by Breazeale and Burgess (1) and by McGeorge and Breazeale (11, 12), and will be given further attention in a series of technical bulletins to be published by the Arizona Agricultural Experiment Station. The only systematic field study of the effects of phosphorus fertilization was made by Crider (5), who showed that lettuce responded to additions of phosphorus. Recent field tests have shown that alfalfa and truck crops often respond to phosphate fertilization.

In the past, fertilizer practice has been limited principally to the application of nitrogen, chiefly in the form of barnyard or green manure. More progressive farmers, however, are commencing to add phosphorus to their soils.

[1] Contribution from the department of agricultural chemistry, Arizona Agricultural Experiment Station.

Consequently there is an apparent need for a method of determining the fertility requirements of these soils. The chemical methods in present use are of little value in determining the availability of fertilizers in these soils. McGeorge (10), in this laboratory, has obtained, to a certain extent, correlation between rate of liberation of phosphate ions during electrodialysis and phosphate availability as determined by the growth of plants. This method has already been discussed (10). The determination of replaceable potassium gives a fair index as to the potassium needs of soils.

The limited value of chemical methods of determining fertilizer requirements of soils has served to stimulate research in biological methods. Christensen (2) in 1907, suggested the use of Azotobacter in mannite solutions, with and without lime, as a means of determining the lime requirement of soils. He later (3, 4) extended this method to test for phosphorus deficiencies in soils, by inoculating a mannite solution of varying phosphorus content with soil. In 1910, Dzierzbicki (6) showed that soils deficient in available lime, phosphoric acid, or potash contained very small numbers of nitrogen-fixing organisms, particularly Azotobacter, and that in some cases these organisms were absent. Stoklasa in 1911 (18) claimed that there is a direct relationship between nitrogen fixed by Azotobacter and the amount of phosphorus assimilated. Niklewski in 1912 (13) presented data showing that an approximation of available phosphorus may be obtained by adding a given amount of soil to a mannite solution free from phosphorus, inoculating with a pure culture of Azotobacter, and then determining the amount of nitrogen fixed at the end of a definite incubation period. Little progress was made in the development of these methods until Winogradsky (20, 21, 22) commenced his studies of nitrogen-fixing organisms. From these studies the spontaneous culture method was developed. A source of energy (usually starch or mannite) is added to a given amount of soil, water is added, and the soil is worked into a thick paste. A quantity of the paste is placed in a Petri dish, the surface smoothed by means of a glass slide, and the plates are then incubated. In approximately 48 hours, Azotobacter colonies commence to appear upon the surface of the soil. Winogradsky found that by the addition of lime, and some soluble phosphate, it was possible to estimate the phosphorus or lime requirements of soils. A comparison of these tests with crop yields gave a close correlation.

Sackett (16) has applied this method to Colorado soils with marked success and recommends its extensive adoption as a routine procedure in determining the phosphorus, potash, and lime requirements of the soils of that state. He has given the method such wide circulation in farm journals, by radio, and before scientific meetings, that it has aroused the interest of Arizona farmers. Although the test, as described by Walker (19), was used in this laboratory in 1929, the results were not sufficiently encouraging to warrant further use. In view of the publicity the method has received recently, a further investigation was made in order to determine its value for determining the mineral deficiencies of Arizona soils.

EXPERIMENTAL

The samples used were taken under aseptic conditions as far as possible, and were stored in sterile containers. These samples represent the principal agricultural sections of the state. A few soils had been used by McGeorge and Breazeale (11, 12) in some phosphate availability studies. These soils were used here because data were available concerning their phosphate contents and the probable phosphate availability, as determined by the electrodialysis method and by pot experiments with plants.

The technique used was that described by Walker (19). Sackett used both sodium and potassium phosphate, in order to estimate both potassium and phosphorus deficiencies, whereas Walker used only sodium phosphate. Since all of the soils examined were calcareous, calcium carbonate was not added. One hundred gram portions of the soil to be tested were weighed into mixing bowls and treated in the following manner:

1. Check—5 gm. potato starch
2. 5 gm. potato starch + 0.6 gm. Na_2HPO_4
3. 5 gm. potato starch + 0.3 gm. K_2HPO_4

The soil and added materials were then thoroughly mixed, and sufficient water was added to make a thick paste. This was then transferred to two halves of 50-mm. Petri dishes, and the surface smoothed by means of a moist spatula. The plates were placed in moist chamber culture dishes and incubated at 30°C. The plates were examined daily. In most soils colonies appeared within 24 to 48 hours; the maximum number appeared within 72 hours. Incubation was continued for 7 days, in order to eliminate the possibility of slow growers, which might otherwise be overlooked. The number of colonies per placque were counted at the end of 72 hours.

The first tests were made upon soils that had been used previously in some nitrogen fixation studies, and were known to contain Azotobacter. Since a relatively large number did not develop colonies on the placques, in order to determine whether Azotobacter were present, 1 gm. of soil was inoculated into 100 cc. of sterile Ashby's medium, and incubated at 30°C. for 14 days. At the end of this period, the flasks containing the medium were examined and the nitrogen was determined by the modified Kjeldahl method. These results appear in table 1.

Since a large number of soils did not develop colonies under any treatment, certain changes were made in the method. Sackett and Stewart (17) recommend that sandy soils be treated with kaolin, that heavy soils be treated with sand, and that basic soils be treated with phosphoric acid in order to promote more favorable conditions. Accordingly a series of soils were treated as follows:

A. Check—50 gm. soil + 2.5 gm. starch
B. 50 gm. soil + 2.5 gm. starch + 0.15 gm. K_2SO_4
C. 50 gm. soil + 2.5 gm. starch + 0.3 gm. $Na_2HPO_4 \cdot 12H_2O$

TABLE 1

Development of azotobacter colonies on placques

SAMPLE NUMBER*	LOCATION	NUMBER OF COLONIES			N FIXED PER GM. MANNITE	REMARKS
		Check	Na_2HPO_4	K_2HPO_4		
					mgm.	
50	Oak Creek Canyon near Jerome. Orchard	0	0	0	9.2	Peach orchard producing well. No P_2O_5 added
53	Little Chino Valley, Prescott	0	0	2	6.1	First year out of desert, planted to peas. Poor growth
51	Big Chino Valley, Prescott	0	12	20	10.7	Plowed from desert, 1929. In corn, excellent growth and yield
43	Rigo Ranch, Prescott	0	0	0	8.2	Dry farmed 17 years, in corn continuously, good yields
26	Mojave Loam, Phoenix	19	100	60	9.0	Fallow
47	Edwards Farm, Clemanceau	0	0	150	12.2	Garden. Heavily manured
31	Michelbach Ranch, Flagstaff	0	0	0	5.0	Potatoes. Poor growth and yield
30	Curry Ranch, Flagstaff	0	0	0	4.2	Heavy stand of oats
35	Duke Ranch, near Meteor Crater	14	30	9	11.8	Good stand of beans
36	Duke Ranch	30	8	20	6.5	Poor stand of beans
32	E. Burrus Ranch, Flagstaff	0	0	0	11.0	Potatoes—good growth
42	Coconino Nat. Forest, Flagstaff	0	0	0	5.7	Typical pine forest soil
46	Bochot vegetable garden, Prescott	0	0	0	9.5	Heavily manured. Excellent yield of vegetables
21	Glendale very fine sandy loam, Phoenix	50	160	80	11.4	Heavy stand of Sudan grass
24	Glendale sandy loam, Phoenix	100	300	400	11.0	Fallow
25	Mojave sandy loam, Phoenix	0	0	0	9.3	Fallow
28	Pima clay, Phoenix	50	400	400	11.5	Cotton. Fine growth
20B	Bradley Ranch, Gila Valley, Yuma	4	200	100	10.8	Heavy soil. Fair stand of alfalfa, due to salt accumulation
38	Edge of Painted Desert, near Winslow	0	0	0	1.0	Typical Red Mesa soil, scant growth, creosote bush, mesquite
16	University Farm, Yuma	0	0	0	6.4	Sandy mesa soil, citrus. Good condition
13	Diller Ranch, Casa Grande	40	120	70	9.3	Very tight, impervious soil
27	Mojave Clay Loam, Phoenix	0	500	500	11.2	Heavy stand of wheat

* Roman numerals designate soils used by McGeorge and Breazeale (11, 12) in some phosphate availability studies.

TABLE 1—*Concluded*

SAMPLE NUMBER*	LOCATION	NUMBER OF COLONIES			N FIXED PER GM. MANNITE	REMARKS
		Check	Na_2HPO_4	K_2HPO_4		
					mgm.	
17	Old Fertilizer Experiment plot, Yuma	200	60	120	9.4	Super phosphate plot citrus trees. Fine condition
37	Pessarra Ranch, Flagstaff	4	6	6	5.7	Good stand of beans
48	Verde Valley, near Jerome	0	0	0	11.5	Fair alfalfa in area damaged by smelter smoke
44	Goff Ranch, Dewey	5	15	15	9.1	Heavy stand corn
I	Tal-wi-wi, Phoenix	30	0	0	9.5	Grapes, heavy phosphate application
II	Same	0	0	0	10.2	No phosphate added
III	Bard, California	0	0	0	8.5	From plot deficient in phosphate
IV	Davis Ranch, Tempe	0	25	100	10.7	Poor cotton, low in phosphate
V	Same	0	200	0	10.3	High in soluble P_2O_5 does not respond to phosphate fertilization
VI	University Farm, Tucson	0	0	0	11.4	Black alkali soil. High in water soluble P_2O_5
VII	Turley Ranch, Tempe	0	150	150	11.0	Poor cotton. Low in soluble phosphate

D. 50 gm. soil + 2.5 gm. starch + 0.15 gm. K_2HPO_4
E. 50 gm. soil + 2.5 gm. starch + 0.085 gm. H_3PO_4
F. 50 gm. soil + 2.5 gm. starch + 10 gm. fine sand + 0.3 gm. $Na_2HPO_4 \cdot 12H_2O$
G. 50 gm. soil + 2.5 gm. starch + 2 gm. $CaSO_4$ + 3 gm. $Na_2HPO_4 \cdot 12H_2O$

Sackett and Stewart (17) state that soils of the "adobe type" must be aerated in order to produce good growth. Gypsum was added to determine whether it would coagulate soil colloids sufficiently to permit development colonies; a method used in the reclamation of "black alkali" soils. A soil of a pH 8.0 or greater would become "puddled" upon the addition of water, and this deflocculated condition would favor the development of anerobic nitrogen-fixing organisms at the expense of Azotobacter. The results of these various treatments are given in table 2.

DISCUSSION

Table 1 shows that out of 33 soils examined, 14 or approximately 42 per cent did not develop colonies under any treatment. Thirteen soils (or 39 per cent) showed a response to sodium phosphate applications, and 16 (38 per cent) responded to treatment with potassium phosphate. Only 7 soils responded more to potassium phosphate than they did to sodium phosphate. All soils, however, with the exception of No. 38 showed the presence of Azotobacter

when inoculated into Ashby's medium. This was demonstrated by the amounts of nitrogen fixed, and by characteristic membrane growth on the medium.

The few soils that did respond to additions of potassium and phosphorus, which indicates a deficiency of these elements, do not always correlate with crop growth. For example, No. 35 and 36 came from the Duke Ranch near Meteor Crater. The tract was planted in beans, yet the sample from the area of best growth gave more response to phosphorus than did the sample from an area of poor growth. Sample 51, which had been plowed from desert only 1 year before, and which had an excellent stand of corn which later gave a fine yield, responded to both phosphorus and potassium. Sample 47 responded only to K_2HPO_4 yet this was a garden soil which had been heavily manured, and which gave good crop yields. Sample I and II gave no response, although I had been given heavy applications of phosphate which showed a crop response in the field, and II is the same soil, untreated. Samples IV and V reflect a similar

TABLE 2

Effect of soil treatments upon colony development

TREATMENT	NUMBER OF COLONIES UNDER SOIL TREATMENT			
	VII	IV	V	VI
A	0	0	0	0
B	0	0	0	0
C	0	0	0	0
D	0	0	0	0
E	0	0	0	0
F	10	20	0	0
G	10	0	0	0

condition; IV, which was deficient in phosphate, did not respond so well to phosphate addition as did V, which contains an abundance of phosphorus, and which (in pot experiments) does not respond to phosphate fertilization. The table shows that only 17 of the soils (51 per cent) developed Azotobacter colonies under any treatment.

Table 2 shows that there was little response to various treatments, although samples VII and IV did respond to additions of sand. On the other hand, No. VI is a typical "black alkali" soil which contains relatively large amounts of soluble phosphate, yet it did not respond to any treatment, although table 1 shows that it contains an active Azotobacter flora.

It is apparent, then, that the proposed methods of Sackett are not applicable to Arizona conditions. In addition to the treatment used in table 2, other placques were made using different carbohydrates as a source of energy, and by adding varying amounts of phosphorus in the forms of different salts. The results, however, were not encouraging.

It is probable that the lack of development of colonies when Arizona soils are used is due to a lack of aeration. It is very difficult to bring many of these alkaline soils to their optimum water content without a "puddled" condition resulting. Although Sackett recommends that H_3PO_4 be added to basic soils (pH 8.4 or greater), the author does not recommend this procedure for Arizona soils. Because of their calcareous nature, the phosphoric acid is rapidly neutralized without bringing any significant change in pH. Furthermore, Burgess[2] has found that there is considerable nitrogen fixation in soils of high pH, as table 3 shows. In these experiments, 2 gm. of soil was inoculated into Ashby's medium, and incubated for 2 weeks at 28°C.; in another series 100 gm. of soil was placed in a tumbler, 1 gm. of mannite added, and incubated for 4 weeks at optimum moisture content. The anerobic fixation was determined by inoculating 1 gm. of soil into 100 cc. of Winogradsky's solution containing 1 per cent of glucose. These solutions were freed from oxygen by placing them in a Novy jar, evacuating, and then filling the jar with nitrogen gas. These results,

TABLE 3

Nitrogen fixation in soils of high pH (data of Burgess)

SOIL	pH	N FIXED PER GRAM OF MANNITE		
		Ashby's solution	Tumbler	Anerobic fixation
		mgm.	*mgm.*	*mgm.*
13	9.55	9.3	10.0	2.1
17	9.0	9.4	21.0	4.3
1a	9.3	17.0	24.0	5.3
6a	9.0	14.9	12.5	4.2
11B	10.0	10.8	20.0	2.2
6C	9.5	14.3	16.5	4.2

which appear in table 3, show that at pH values as great as 9.5 or 10.0, there is active nitrogen fixation.

The work of McGeorge and Breazeale in this laboratory is constantly changing our ideas concerning the availability of phosphorus in calcareous soils. One of the most striking observations is that some of the "black alkali" soils contain more soluble phosphorus than do fertile soils from non-calcareous regions of the United States. Another observation is that aeration has a pronounced effect on phosphate availability. Consequently, the mixing of a heavy soil with sand, or a light soil with kaolin, as Sackett recommends, is sufficient alone completely to alter the availability of phosphorus in the soil.

In general, the results given in tables 1 and 2 do not agree with the description of crop growth. All of these samples were taken by the author, so the remarks concerning the crops are the result of personal observation. The phosphate content of soils I–VII has been determined by McGeorge by use of

[2] Unpublished data from this laboratory.

the electrodialysis method and by pot experiments. Of the 33 soils examined, only 4 (12 per cent) gave results which agree with field observations, and consequently might be an index of fertility needs.

Walker (19) obtained encouraging results with this method in Iowa; Sackett and others have employed it in Colorado; Niklas and his coworkers in Germany have recommended it; and Guittonneau (9) in France has claimed excellent correlation with field conditions. The results of these experiments show, however, that it has but slight value for determining the mineral deficiencies of Arizona soils. These aforementioned investigators were working with soils which were not as highly calcareous, so their positive findings are not applicable to the soils of Arizona, which are usually highly calcareous and often have high pH values and high salt concentrations. This is especially true in the light of the results of McGeorge and Breazeale, which are to be published later.

Pittman and Burnham (14) have not found this test to be reliable in Utah. They found only about 70 to 80 per cent agreement between the test and the field response. This was only in extreme cases where the soil was either very deficient or well supplied with phosphorus. In the intermediate ranges, the correlation was lower.

In spite of the results of various workers, the author is inclined to agree with Pittman and Burnham (14) that this is not a good test for potassium needs, and furthermore believes that it has never been definitely established that Azotobacter have the same food requirements as higher plants, or in the event that they do, certain requirements are so small that such a test can only be a rough index at best.

Greaves (7) states:

> Potassium is essential to the higher plants and cannot be replaced entirely by related substances, yet Gerlach and Vogel early reached the conclusion that potassium and magnesium are not essential to the Azotobacter .... If these elements are essential, it must be in extremely minute amounts, for Vogel, using the purest chemicals obtainable, was able to prepare potassium-free media in which the Azotobacter developed. He did find, however, that potassium favors their development.

In order to determine the need of potassium by Azotobacter, the following experiment was conducted:

> Flasks containing 100 cc. of sterile Ashby's medium were inoculated with suspensions of Azotobacter, incubated for 2 weeks at 30 C., and then analyzed for nitrogen. Another medium was prepared which had the same composition as Ashby's medium except that Na_2HPO_4 was used in place of K_2HPO_4. The pH of each media was 7.8. This series was incubated under the same temperature as the cultures in Ashby's medium. The medium was prepared from C. P. chemicals and was tested for the presence of potassium.

Only traces (less than 0.5 p.p.m. K) were found. The results are given in table 4.

The quantities of nitrogen fixed are practically as great in the presence of minute traces of potassium as in Ashby's solution. This shows that the

amount of potassium required by the Azotobacter is extremely small. Assuming the weight of the surface $6\frac{2}{3}$ inches of an acre of soil to be 2,000,000 pounds, 0.5 p.p.m. K would be only 1 pound of K an acre.

TABLE 4

Milligrams of N fixed by azotobacter per gram of mannite

CULTURE	AMOUNT OF K PER GRAM OF MANNITE	
	Less than 0.05 mgm.	22 mg. (Ashby)
A. agilis	12.6	13.3
A. vinelandii	9.0	9.8
A. chroococcum	9.6	9.6
A. Beijerinckii	9.2	9.0
A. vitreus	1.5	1.5
A. Woodstownii	1.2	1.2

TABLE 5

Influence of phosphate on nitrogen fixation

(Data of Ranganathan and Norris)

CULTURE	MGM. P_2O_5	MGM. N FIXED PER GRAM OF DEXTROSE
A. chroococcum	0	0
	4.2	4.8
	10.2	5.0
	20.8	5.4
	41.6	5.6
	52.0	6.0
	104.0	6.0
50 (from an Arizona soil)*	0	0
	2	6.8
	4	8.0
	6	7.0
	8	5.5
	10	5.6
	20	5.0
	40	4.4
	80	6.0
	100	4.9

* Data of Burgess.

Table 5, which is compiled from data of Ranganathan and Norris (15) and from the unpublished results of Burgess, shows the relation between increasing amounts of phosphorus and nitrogen fixation, by pure cultures of Azotobacter, in dextrose—Ashby's solution.

Although Ranganathan and Norris (15) did obtain increasing nitrogen fixation with increasing amounts of phosphorus, Burgess did not. The latter did show, however, that a small amount of phosphorus is necessary, as shown by the greatest fixation when 4 mgm. of P_2O_5 was added. Although Burgess did not obtain increased fixation with additions of more than 4 mgm. of P_2O_5 this should not imply any contradiction with the results of Ranganathan and Norris, but seems to point clearly to an adaptation of the Azotobacter in Arizona soils. They have become adapted to a minimum of available phosphorus, and hence respond to minute amounts. The author has shown that the Azotobacter flora of Arizona soils have adapted themselves to higher temperatures and can fix nitrogen at greater temperatures than can cultures from more temperate regions (8), so it does not appear too far fetched to assume adaptation to minute amounts of phosphorus.

Apparently the Azotobacter are less sensitive to phosphorus than to potassium. If the lower limit of Azotobacter growth is less than 2 mgm. of P_2O_5 in 100 cc. of a 1 per cent dextrose-Ashby solution; at the same rate, the minimum quantity of available P_2O_5 in the surface $6\frac{2}{3}$ inches of an acre of soil would be less than 40 pounds, which is probably low enough to require phosphate additions in order to produce good plant growth.

It seems, then, that the value of the placque method is limited chiefly to soils which are extremely deficient in phosphorus, which is in agreement with the findings of Pittman and Burnham (14).

SUMMARY

1. The Azotobacter (placque) method of determining mineral deficiencies in soils has been applied to a number of soils of known crop producing powers which represent the principal agricultural sections of Arizona.

Thirty-three soils were examined; thirty-two developed characteristic Azotobacter films on Ashby's solution, and fixed considerable amounts of nitrogen.

Fourteen soils (42 per cent) did not develop Azotobacter colonies on the placques under any conditions. Nineteen soils (57 per cent) developed colonies.

The mineral deficiencies of the soil as determined by the Azotobacter method definitely agreed with field observations only in the case of four soils (12 per cent).

The minimum potassium requirements of Azotobacter are so small that this test is not a good index of potassium needs of a soil.

Azotobacter appears to have a higher minimum requirement for phosphorus than for potassium. From the data submitted, this test is of value only in the case of soils extremely deficient in phosphorus.

This test is of little value in determining the potassium and phosphorus requirements of the soils of Arizona, which are characterized by relatively high pH, their calcareous nature, and an active Azotobacter flora which has become adapted to these conditions.

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THE MICROBIOLOGICAL POPULATION OF PEAT[1]

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The problem of the occurrence and abundance of different types of microorganisms in peat has recently received renewed attention, primarily in connection with the rôle of these microörganisms in the formation of peat from the plants and plant residues inhabiting the peat bog or brought into it. This renewed interest is primarily due, first to the various theories concerning the origin of coal, which takes place presumably through the peat stage, especially whether the lignins or the celluloses of the plant residues form the mother substances of coal; and, second, to the renewed interest in the age-old problem, whether the decomposition of organic residues is microbiological in nature or chemical. It has usually been assumed in the past that peat is a sterile medium, and when it was demonstrated that numerous microörganisms are found in peat, the question was asked whether they are just accidental invaders or whether they play an important function in peat formation. This discussion is similar to others in the past whether certain processes are microbiological or chemical in nature. Since the time of Pasteur, when the famous battle was fought between the bacteriologist and the chemist concerning the nature of fermentation, discussions of a similar nature continued to come up whenever the rôle of microörganisms in a process previously little understood had to be established. The problem of the origin of peat and the rôle of microörganisms in its formation and transformation will occupy a certain definite place, even if only a modest one, in the history of microbiology.

The problem of the relation of microörganisms to peat formation can be definitely summarized by the following questions: 1. Are microörganisms found in different layers of peat bogs laid down many years ago? 2. If they are found there, how abundant are they, and are they in an active state? 3. Do they continue to decompose the peat? 4. What part have they played in the formation of peat from the plant residues? 5. What part do they still play in the processes of continuous transformation of peat, if such take place?

Waksman and Stevens (13) have already shown that there is no justification

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whatsoever for considering a peat bog as a sterile medium, as was frequently done by many botanists, geologists, and chemists, but that it is teeming with life. In certain bogs, as in the highmoor peats, there is not only no diminution in the number of bacteria with an increase in the depth of the peat formation, but frequently there may be a very decided increase. The bacteria found in the lower depths of the bog seemed to comprise largely certain specific types capable of growing in rather acid (of pH 3.8–4.0) media, and capable of living both aerobically and anaerobically. Evidence was submitted to prove that the processes of inital decomposition of the plants at the surface of the bog and their further transformation into peat are primarily microbiological in nature.

That study was undertaken without any preconceived idea of proving or disproving any particular theory. However, the results were used by Fischer (5) and Lieske (7), on the one hand, and the opponents of the "lignin theory of the origin of coal" (2, 9), on the other, to prove or disprove the lignin theory. These results and other studies carried out in this laboratory and dealing with the chemistry of peat (11, 12) tended to demonstrate that this theory is to a certain extent justified, but that it is very one-sided and that it tells but a part of a very complicated story. Although it is true that the lignin is very resistant to decomposition by microörganisms, especially under the conditions prevailing in the peat bogs, namely, under anaerobic conditions, it never makes up more than a part of the total organic constituents of the peat, even in the most advanced stages of decomposition. Further, although in certain peats, as in sedimentary and lowmoor peats, the cellulose tends to disappear as a result of its slow but gradual decomposition by microörganisms, a fairly large quantity of hemicelluloses is still left.

The amount of protein that may be present in certain peats is very considerable, making up frequently over 20 per cent of the total organic constituents of these peats. The parallel increase that may be observed between the protein content and the decrease in the concentration of cellulose is a direct result of microbial synthesis, which always accompanies microbial decomposition and energy utilization.

It should be emphasized here that the nature of the plants which give rise to peat and the conditions in the bog (such as reaction and mineral content) under which the decomposition of the plant residues takes place, are of the greatest importance in determining the nature of the peat produced. One cannot compare readily a lowmoor peat with a highmoor peat, since they differ botanically, chemically, and microbiologically. The lowmoor peats, as well as the forest peats, show very marked signs of microbiological decomposition, which can be characterized as follows: a very rapid reduction in the cellulose content to almost complete disappearance, depending upon the age of the peat layer; a marked reduction of the hemicelluloses, with the non-pentosan hemicelluloses (largely uronic acid compounds) predominating in the decomposed peat, as compared with their relative abundance in the initial plants; an in-

crease in the protein and ash content, as compared with the original plant residues, this increase being parallel with the decrease in the cellulose, a large part of the protein being a result of microbial synthesis; a marked increase in the content of lignin and lignin-like complexes. These peats offer a favorable medium for microbial development and, when drained, offer an excellent medium for the development of higher plants. The chemical composition of this type of peat tells the story of its formation, as well as the rôle of microörganisms in the processes involved.

Highmoor peats, which have been formed predominantly of sphagnum plants, on the other hand, show totally distinct chemical characteristics: they are rich in cellulose and hemicelluloses; whether as a result of the physical nature of the plants, or the specific nature of their chemical constituents, they are highly resistant to decomposition, especially the carbohydrates and the lignins. However, the organic nitrogenous compounds in the sphagnum plants can undergo rapid decomposition, with the result that a marked reduction in the protein content is found; because of the resistance to decomposition of the carbohydrates in the sphagnum plants, especially under anaerobic conditions, there is also only a very limited increase in the ash content, frequently preceded by a decrease. Only when a dry period prevails for a considerable period of time will the aerobic conditions and the introduction of a new type of vegetation result in a change in these properties, such as an increase in the ash and protein content, as in the case of the Grenhorizont; the lignin content gradually increases with the increase in age of the peat, and the cellulose content decreases. This type of peat, once it is fully saturated with water, is a very poor medium for bacterial development, although far from being sterile; it offers also a poor medium for the growth of higher plants, even when drained, unless the reaction is corrected by the use of lime, and the needed nitrogen and mineral constituents are added.

In order to illustrate the fact that the microbiological activities in a lowmoor peat are markedly influenced, if not completely controlled, by environmental conditions and by the presence of available energy, the results presented in tables 1 and 2 will suffice. In one experiment 500-gm. portions of fresh lowmoor peat, obtained from Florida, were partially dried down, so as to adjust the peat to different moisture content, and the microbiological activities, as measured by the CO_2 evolution, as well as the amount of mineralized nitrogen, were compared. Certain definite differences were obtained (table 1), showing that by changing a single factor, such as moisture content, marked differences will be obtained in the rate of peat decomposition.

In another experiment, 100-gm. portions of lowmoor peat from Florida, containing 80 per cent moisture, were placed in flasks. Four flasks were left untreated, four were treated for 48 hours with toluol, four for 48 hours with ether, and four with 2 per cent HCl; the last set was then washed with water and brought back to original moisture. All the flasks were inoculated with fresh soil suspension and incubated for 20 days. The CO_2 given off was measured

at frequent intervals. At the end of the incubation period, the NH_3 and NO_3 produced and the numbers of bacteria and fungi present in the different flasks were determined (table 2).

The results show clearly that the various modifications of the peat have a marked effect in changing it as a medium for microbial activities. The changes produced depend entirely upon the nature of the treatment. When the treatment brings about a suppression of the fungi, as in the case of the toluol-treated peat, there is a small increase in bacterial development accompanied by a small increase in CO_2 evolution and nitrogen libration. Where the treatment results in a condition favoring fungous development, as in the ether-

TABLE 1

*Influence of moisture content upon the decomposition of peat**

MOISTURE IN PEAT	CO_2 GIVEN OFF	NITROGEN MINERALIZED
per cent	*mgm.*	*mgm.*
81.5	820	6
80.2	1,183	10
71.3	2,966	82
52.8	2,886	92
33.3	775	26

* 500 gm. of peat of 81.5 per cent moisture; incubation 188 days.

TABLE 2

Influence of treatment of peat upon its decomposition

TREATMENT	CO_2 GIVEN OFF	NH_3—N	NO_3—N	TOTAL NITROGEN MINERALIZED	BACTERIA*	FUNGI*
	mgm.	*mgm.*	*mgm.*	*mgm.*		
Untreated	36.1	2.34	11.18	13.52	21,000,000	235,000
Toluene-treated	62.1	7.70	7.50	15.20	24,250,000	52,000
Ether-treated	204.8	7.74	0.43	8.20	97,000,000	7,100,000
HCl-treated	145.8	14.57	0.55	15.12	105,500,000	359,000

* In 1 gm. of moist peat.

treated peat, there is a much greater increase in the rate of decomposition, as shown by the CO_2 evolution, but this is accompanied by a reduction in available nitrogen, due to the extensive synthesis of fungous mycelium. The mild acid treatment results in a favorable effect upon the decomposition of the peat and in a marked bacterial multiplication. However, this is accompanied only by a small increase in the available nitrogen, due possibly to the fact that this treatment was also partly favorable to fungous development.

Without going into a discussion of the underlying chemical and microbiological phenomena resulting from these treatments, it is sufficient to emphasize the fact that the microbial development in peat is markedly influenced by the

physical and chemical conditions of the peat and by the environmental conditions.

As to the influence of the chemical composition of the highmoor peat upon its decomposition, the following experiment will be of interest (table 3). Fresh sphagnum plants were dried and divided into three parts: one part was left untreated; one part was treated with 4 per cent sodium hydroxide solution for 5 hours in flowing steam, to remove the lignin and some of the hemicelluloses; a third part was treated with the hot alkali solution followed by hydrolysis with 2 per cent hot hydrochloric acid, for 5 hours in flowing steam, to remove most of the remaining hemicelluloses. The preparations were washed with distilled water and dried. Five gram quantities of the dry sphagnum preparations were added to 150-gm. portions of sand placed in Erlenmeyer flasks.

TABLE 3

*Decomposition of sphagnum plants, as influenced by removal of certain chemical complexes**

	CO_2 LIBERATED	CONTROL SUBTRACTED	AMMONIA FORMED	NO_3—N LEFT	TOTAL MINERALIZED N PRESENT	NITROGEN LIBERATED (+) OR CONSUMED (−)	RATIO BETWEEN CARBON LIBERATED AS CO_2 AND NITROGEN CONSUMED OR MINERALIZED (C/N)
	mgm. C	*mgm. C*	*mgm. N*	*mgm. N*	*mgm.*	*mgm.*	
Control	11.5	.....	2.2	27.8	30.0	.....	7.8
Sphagnum alone, without nutrients	148.4	136.9	14.4	3.2	17.6	+17.6	10.1
Sphagnum + nutrients	142.9	131.4	15.4	27.6	43.0	+13.0	....
Sphagnum extracted with hot 4 per cent NaOH	273.3	261.8	1.8	15.0	16.8	−13.2	20.7
Sphagnum extracted with 4 per cent NaOH and 2 per cent HCl	393.4	381.9	1.6	2.0	3.6	−26.4	14.5

* These results are taken from experiments carried out by Mr. H. W. Reuszer of this laboratory.

Each flask, with the exception of the nutrient-free cultures, received 200 mgm. $NaNO_3$, 100 mgm. K_2HPO_4, and 40 cc. of distilled water. All the flasks were inoculated with a suspension of good garden soil, placed in an incubator at 27–28°C. and connected with a respiration apparatus. At the end of 46 days' incubation, the flasks were discontinued and the ammonia and nitrate nitrogen determined. The results show that the decomposition of the untreated sphagnum plants proceeds very slowly, since only about 145 mgm. of carbon were given off as CO_2 from the decomposition of 5 gm. of material, in a period of 46 days. However, the fact that as a result of this decomposition, nitrogen was also liberated in appreciable quantities and the fact that the addition of available nitrogen as nitrate had no favorable effect upon the rate of decomposition shows: 1. that the nitrogenous complexes in the sphagnum plants decompose

very readily, 2. that the carbohydrates (cellulose and hemicelluloses) are resistant to decomposition, 3. that because of this, little microbial synthesis takes place, and 4. as a result of this, the liberation of nitrogen in an available form takes place. The sphagnum plants which have been treated with an alkali and especially the material treated with both the alkali and acid, whereby most of the lignin and hemicelluloses were removed (nearly 80 per cent of the material was removed by both treatments), decomposed much more readily, as shown by the rate of CO_2 evolution and nitrogen consumption. In this respect the sphagnum material behaved as residues of higher plants low in nitrogen usually do.

Thaysen (9) considers the existence of bacteria in deep layers of peat, laid down thousands of years ago, as totally anomalous; such an attitude toward the ability of anaerobic bacteria to exist in an anaerobic medium for long periods of time is totally unjustified; this idea is on a par with the claim of "the presence in the water of the bog of substances such as organic acids . . .", although nobody established the presence or formation of such acids in any significant amounts. The non-existence of such acids has been shown by Baumann and Gully (1). It is not only the acid conditions of the highmoor peat that make it a poor medium for the growth of microörganisms but the resistance of the organic substances of the sphagnum and other plants to decomposition. The lowmoor peat, which is much less acid, and which has originated from plants more readily decomposable usually contains a much more abundant flora of microörganisms. However, even the acid peat harbors an extensive flora of bacteria capable of living under the acid conditions prevailing in the bog, as shown later.

The numbers of bacteria found in different depths of a lake peat from Florida are given in table 4; the surface of this peat was 90 cm. below the surface of the water. The results show quite definitely that peat contains appreciable numbers of bacteria capable of living under aerobic and anaerobic conditions. Although these organisms are most abundant in the surface layers of the peat, where the organic residues are of recent origin and, therefore, undergo active decomposition, still the lower layers contain appreciable numbers of bacteria. This peat was free from fungi even in the surface layers, since the latter were deep under water. However, in the case of lowmoor peats, especially those that are partly drained, the surface of the peat will be found to contain large numbers of fungi and especially actinomyces (table 5).

In arguing against the activities of the bacteria in the older layers of peat, Thaysen questions their functions, since only few cellulose-decomposing bacteria, if any, were found. In this respect one must always examine the chemical composition of the peat; one can hardly expect many cellulose-decomposing organisms in a medium free from cellulose. The methods used for determining the presence and abundance of anaerobic cellulose-decomposing bacteria in a certain natural substrate have been one of the stumbling blocks in bacteriology. As a matter of fact, even after 80 years of investigation, since

Mitscherlich first announced the discovery of the anaerobic cellulose-decomposing bacteria (which later proved to be incorrect), even 30 years after Omeliansky's classical studies on these bacteria, we are still uncertain as to the actual isolation of pure cultures of these organisms, notwithstanding the excellent work of Khouvive, Warner, Fred, and others. The methods for demonstrating the presence of cellulose-decomposing bacteria, especially of anaerobic forms, depend largely upon the natural medium in which these organisms grow, such as soil, animal digestive tract, sea water, stable manure, and peat bogs.

TABLE 4

Distribution of bacteria in the peat profile of Algal Lake, Florida

DEPTH OF LAYER	MOISTURE CONTENT	pH	ASH IN DRY MATERIAL	AEROBIC BACTERIA		ANAEROBIC BACTERIA	
				1 gm. of moist peat	1 gm. of dry peat	1 gm. of moist peat	1 gm. of dry peat
cm.	*per cent*		*per cent*				
Surface*	97.8	7.5	18.8	360,000	16,820,000	200,000	9,090,000
60	97.8	7.6	24.4	82,000	3,727,000	150,000	6,820,000
90–120	90.9	7.3	39.6	25,000	275,000	80,000	879,000
150–180	91.5	7.1	23.3	28,000	329,000	180,000	2,118,000
210–270	95.5	7.2	8.8	60,000	1,334,000	160,000	3,556,000
300–360	94.2	7.3	14.7	450,000	7,930,000	180,000	3,103,000

* 3 feet below surface of water.

TABLE 5

Numbers of microörganisms in an undrained peat bog in Florida

Numbers in 1 gm. of moist peat

DEPTH OF PEAT	MOISTURE	AEROBIC BACTERIA	ACTINOMYCES	FUNGI	ANAEROBIC BACTERIA
cm.	*per cent*				
2–20	80.1	890,000	370,000	20,000	120,000
22.5	82.9	960,000	290,000	10,000	180,000
45	85.3	410,000	100,000	7,000	180,000
75	84.0	18,000	13,000	330	16,000
120	85.4	30,000	330	0	75,000
165	87.4	235,000	3,330	0	380,000

One is fortunate enough in being able to demonstrate the presence of these organisms, even if in limited numbers. Positive results are definite proof that the organisms are present. Negative results do not always necessarily prove that the organisms are absent. One would be more inclined to think that negative results may possibly be due to the inappropriate methods employed in searching for these organisms.

In the case of two typical lowmoor peats, one obtained from Newton, New Jersey, and the other from the Everglades, Florida, cellulose-decomposing bacteria have been demonstrated throughout the profile, including the lowest lay-

ers. The fact that these organisms decrease in numbers with depth can probably be accounted for by the mere traces of cellulose left below the surface of these peat formations. The fact that these organisms are found in the lower layers of these peats may be due not only to the traces of cellulose present, but to the ability of some of them to attack hemicelluloses as well, as was found to be the case of various cellulose-decomposing bacteria in the soil (6).

Another observation, which may prove to be of considerable importance for our knowledge of the decomposition of the organic complexes in lowmoor and sedimentary peats, is the discovery of certain actinomyces, which have been isolated from depths of 135 cm. below the surface of the bog in the Everglades, Florida, or about 100 cm. below the surface of the water table. These actinomyces are facultative anaerobic, have an optimum temperature at 40–42°C., attack cellulose, and are capable of attacking the organic complexes of the peat, under anaerobic conditions, without liberating any gases. Plate 1 illustrates the abundance of actinomyces mycelium that may be found in peat. This particular clump of peat came from a surface layer, however. The determination of the abundance of actinomyces by the plate method gives only a very faint idea of the extent of development of these organisms.

These results may be considered as definitely establishing the occurrence of cellulose-decomposing microörganisms throughout the profile of the lowmoor peat bogs as well as the fact that the removal of the cellulose, in the process of formation of these peats, is due entirely to the action of microörganisms.

Sedimentary peats and forest peats present somewhat different relationships in that the former contain very little cellulose even at the beginning of the process of peat formation, whereas the latter contain some cellulose even in the peat stage, which is still in the process of active decomposition.

The most interesting problem, however, in connection with peat formation and peat decomposition, is that of the highmoor peats. This is due both to the abundance of these peats in the northern regions of Europe and to the fact that they have been largely used by those investigators who usually reported negative results concerning the activities of microörganisms in peat formation. A highmoor peat consists of a layer of sphagnum peat, of varying degrees of thickness, formed directly upon an inorganic substrate, or superimposed upon a layer of sedimentary peat (Gyttja, Dy), sedge or reed peat, or forest peat.

An analysis of the chemical composition of peat in different depths of a highmoor profile (12) will reveal the fact that chemically the nature of the particular layer of peat depends entirely upon the plants and plant residues from which it has been formed. The sedimentary layer, the sedge or reed peat layer, and the forest peat layer in highmoor peats will be similar in composition to that of the corresponding peats, namely the sedimentary, lowmoor, and forest peats, as shown by the low cellulose content, high mineral content, high protein content, and high lignin content. On the other hand, the sphagnum layers, usually many feet thick, which give the characteristic properties to the

highmoor peats, are distinctly different in chemical composition. The sphagnum layers are rich in cellulose and hemicelluloses; they are low in ash and in protein; they contain a moderate concentration of lignin or lignin-like substances, depending upon age; they are distinctly acid in reaction. As a matter of fact, on comparing the chemical composition of sphagnum peat with fresh sphagnum plants, from which such peat originated, one will observe that, with two exceptions, the relative composition is quite similar, unless the particular layer of peat has undergone aerobic decomposition due to a continuous dry period, as in the formation of the Grenzhorizont. The two exceptions are the lower nitrogen content and the greater lignin content; the former is due to the presence of readily decomposable nitrogenous compounds in the sphagnum plants and the difficultly decomposable carbohydrates, as a result of which there is little synthesis of microbial cell substance.

These phenomena can readily explain the difference in the nature of the microbial populations in the various peats. The sphagnum layers of the highmoor peat, below the surface layers, are poor in microörganisms, especially in cellulose-decomposing bacteria. This is due largely to the fact that the reaction (pH 4.0 or less) is highly unfavorable to the growth of such bacteria (4). Further, the specific form in which the cellulose and hemicelluloses exist in the sphagnum plants renders them highly resistant to the action of such bacteria. The anaerobic conditions are unfavorable to the development of the fungi. However, one is not justified in applying these facts to peat bogs in general and even to all the layers of highmoor peats. In order to show that such generalizations are not only unjustified, but quite wrong, further experimental evidence will be presented. For this purpose, certain of the studies on the distribution of microörganisms in the highmoor peats from Maine, carried out in the summer of 1928, were repeated again in 1931. One of these bogs, namely the Cherryfield or Denbo heath, is known to have never been disturbed by man.

The Denbo heath (3), located northwest of Cherryfield, Maine, has a typical dome-shaped surface, which rises from the margin of the bog to the center. The vegetation of the bog is made up largely of various species of *Sphagnum* (*S. tenellum*, *S. acutifolium*, *S. megallanicum*), with an admixture of species of *Eriophorum*, *Scirpus*, *Vaccinium*, *Drosera*, etc. The bottom of the bog, where the samples were taken, was reached at about 21 feet. The sphagnum peat extended to a depth of 15 to 17 feet; below that there was a layer of sedge peat superimposed upon a sedimentary layer (detritus gyttja), with a compact sandy bottom.

The Orono or Veazie bog is located outside of Orono, Maine. It is only slightly convex, is a shallower bog, and is not a typical highmoor. The *Sphagnum-Eriophorum* layer is only about 5 to 6 feet thick, superimposed upon woody peat with a clay-gyttja bottom, upon compact sand, the whole bog being about 12 feet deep.

Samples were obtained from a number of depths of these two bogs and put into a series of sterile glass jars. For bacteriological studies the inner part of

the core was used. However, the fact that the numbers of bacteria do not diminish with depth, but markedly increase (table 7) is sufficient evidence that no contaminating material could have been brought down with the sampling tube from the surface.

The reaction, moisture, ash, and nitrogen content of the Denbo profile are given in table 6, and the distribution of microörganisms in this profile is shown

TABLE 6

Physical and chemical conditions of the Cherryfield or Denbo peat profile

DEPTH OF PEAT	MOISTURE CONTENT	pH	ASH IN DRY PEAT	NITROGEN IN DRY PEAT
cm.	*per cent*		*per cent*	*per cent*
Surface	82.1	4.0	4.24	0.875
5	89.5	4.1	1.52	0.595
30	91.7	4.0	1.07	0.527
45	90.9	4.0	1.53	0.777
75	92.4	3.9	0.92	0.754
195	94.3	4.2	1.56	0.620
330	94.4	4.2	1.83	0.586
450	93.8	4.3	1.61	0.644
570	85.9	5.0	88.47	0.624
570	70.9	5.2	74.55	0.555

TABLE 7

Chemical composition of the Denbo peat profile

On per cent basis of dry material

DEPTH OF LAYER	ETHER-SOLUBLE	HOT WATER-SOLUBLE ORGANIC MATTER	HEMICELLULOSES	CELLULOSE	LIGNIN
cm.					
Surface	2.43	2.15	22.60	16.04	30.85
5	2.70	1.61	24.34	17.09	25.20
30	1.93	2.06	25.94	16.06	24.71
45	2.30	1.52	22.36	14.02	29.30
75	2.47	1.16	21.41	14.83	28.73
195	....	....	.....	.....	.....
330	5.07	2.09	17.46	12.33	34.44
450	5.04	2.60	14.97	10.87	37.04
570	0.65	0.22	Trace	Trace	8.35
570	1.55	0.52	1.83	Trace	17.67

in table 7. The reaction remains more or less uniform (pH 3.9–4.2) throughout the depth of the sphagnum layer; this is accompanied by a uniformly low ash and nitrogen content. However, as soon as the reaction of the peat increases above pH 4.3, or becomes less acid, there is an accompanying increase in the ash and nitrogen (on ash-free basis) content, showing that a change of the sphagnum peat into a sedge or reed peat, or into a forest or sedimentary peat, has taken place. This has been confirmed by botanical examination.

The chemical composition of this peat profile is given in detail in table 7. However, the important point to emphasize in connection with this profile is the change in the abundance of microörganisms with a change in the chemical composition of the peat (tables 7 and 8).

As long as the reaction of the bog is pH 4.0 and the peat is the typical sphagnum of the highmoor type, the numbers of bacteria remain low. However, as soon as the reaction becomes less acid and the vegetation from which the peat has been formed changes, there is a rapid rise in bacterial numbers. These numbers were determined by the plate method, using a medium consisting of 5 gm. peptone, 10 gm. glucose, 0.5 gm. $MgSO_4 \cdot 7H_2O$, 1 gm. K_2HPO_4, and agar. By the use of the shake tube method, large numbers of anaerobic, gas-forming and non-gas forming bacteria were also obtained. Plate 2 gives a pictorial representation of the relative distribution of bacteria with

TABLE 8

Distribution of bacteria in a highmoor peat profile in Maine (Cherryfield)

DEPTH OF PEAT	NUMBERS OF MICROÖRGANISMS PER 1 GM. OF MOIST MATERIAL		BACTERIA IN 1 GM. OF DRY MATERIAL
	Bacteria	Fungi	
cm.			
Surface	50,300	57,000	281,000
5	197,000	30,000	1,876,000
30	33,000	2,000	400,000
45	21,600	1,000	237,000
75	766,000	0	10,350,000
195	2,260,000	0	39,650,000
330	3,293,000	0	58,800,000
450	3,006,000	0	48,500,000
570	5,513,000	0	39,100,000
570	4,800,000	0	16,500,000

increasing depth of the Denbo peat bog, using a dilution of 1:50,000 on the fresh moist peat. The actual numbers are reported in table 8.

During the process of taking the samples of peat, when the borer was introduced into the bog, and especially when a depth of about 350 cm. was reached, as well as below that layer, abundant gas evolution took place. This gas took fire readily. Although small quantities of gas came up also from the higher, or sphagnum layers of the peat, the most abundant evolution of the gas seemed to coincide with the abundant development of bacteria, as shown by the plate method, and with the presence of anaerobic gas-forming bacteria, as determined by the shake tube procedure.

The chemical composition of the Orono peat is given in table 9, and the numbers of bacteria are reported in table 10. A change from the sphagnum to the sedge and forest peat is found at a depth of between 60 and 180 cm. This is accompanied by a change in ash and nitrogen content, in the composition of the organic constituents, and in the numbers of microörganisms.

These results should entirely dispose of the unjustified and misleading assumption of the sterility of peat, as well as of the hypotheses concerning the purely chemical processes involved in the transformations that presumably predominate in peat bogs. The authors do not want to deny in the least that, under certain conditions, as in the sphagnum layers of the highmoor peats, chemical processes, especially those of weak hydrolysis and reduction, may take place, as a result of the great resistance of these organic complexes to microbial decomposition and of the unfavorable conditions for the abundant development of many organisms. There is no need, however, for assuming, as

TABLE 9

Physical and chemical conditions of the Orono peat profile

DEPTH	MOISTURE	pH	ASH IN DRY MATTER	NITROGEN IN DRY MATTER
cm.	*per cent*		*per cent*	*per cent*
3–5	96.9	4.0	6.34	0.665
20	92.3	4.2	2.04	1.057
60	95.7	4.6	2.04	0.938
180	94.4	5.3	5.71	1.604
300	92.0	5.8	12.31	1.765
330	79.8	6.1	68.42	0.690
330–360	72.5	6.0	70.72	0.425

TABLE 10

Distribution of bacteria in a highmoor peat profile in Maine (Orono)

DEPTH OF PEAT	BACTERIA IN 1 GM. OF MOIST PEAT	BACTERIA IN 1 GM. OF DRY PEAT
cm.		
3–5	27,600	890,000
20	230,000	3,240,000
60	7,000,000	162,800,000
180	4,080,000	72,800,000
300	5,100,000	63,700,000
330	7,000,000	34,600,000
330–360	8,000,000	29,100,000

Lieske (8) has done, that in such bogs, the celluloses are hydrolyzed chemically to sugars and the latter enable the organisms to grow. That such an assumption is also totally unjustified is revealed by an examination of the data on the chemical and microbiological conditions of the lower layers of the bogs. But even in the sphagnum layers, this assumption is not justified, because of their very high cellulose content.

A number of cultures of bacteria, largely facultative anaerobic forms, characteristic of the various types which developed on the plate or in the tubes, were isolated, and grown in pure culture. Since these bacteria were isolated from samples of peat taken from various depths of the highmoor and lowmoor pro-

files, they are believed to represent typical bacteria inhabiting those peats. Most of these bacteria produce gas when grown in liquid media containing glucose. Although there is no doubt that some of these bacteria have never before been described, the mere naming of organisms, the functions of which in natural processes still remain to be determined, is of questionable value. The group of cultures were, therefore, studied only in a very general way, without any attempt to describe them in detail.

Most of them were non-spore-forming short rods, with rounded ends, to almost spherical organisms, about a micron in diameter and a little over a micron long. Most of these bacteria were gram-negative, non-motile or motile. Some were gram-positive. A few larger rods, about 2μ long, forming diploids, were also found. Physiologically they were characterized by the readiness with which they grew in acid media, of pH 4.0. Some were proteolytic, as determined by their ability to liquefy gelatin and digest casein in milk, others were only weakly proteolytic. Some produced active diastatic enzymes, others did not. Most of them grew readily on synthetic media with glucose or sucrose as sources of energy. When freshly isolated, some produced on synthetic media (glucose agar) and on nutrient agar, an abundant cream-colored to brown and frequently dark-brown, slimy growth. They were isolated from dilutions ranging from 1,000 to 10,000, from all depths of the peat profiles, especially from the sedge and reed layers, usually at a depth, in the case of the highmoor peats, of 165 to 540 cm.

In addition to the facultative anaerobic bacteria, certain yeasts and various obligate anaerobes were isolated from the peats. No attempt will be made to describe these organisms either. The anaerobes were found to be rod-shaped, spore-forming or non-spore-forming, motile or non-motile organisms. Several cellulose-decomposing bacteria were isolated. This could best be accomplished by spreading some peat in a sterile Petri dish and pressing upon the surface of the peat strips of sterile filter paper. If cellulose-decomposing bacteria are present, they will attack the paper, changing it to a slimy consistency and producing rose, pink, yellow, and dark pigments on the paper.

The common procedure of inoculating liquid or solid (especially silica-gel) media containing paper as the only source of energy with the various peat materials frequently gives negative results, which cannot be taken as definite proof of the absence of such organisms. The media are to be considered as unsuitable for the development of such organisms. By modifying the composition of the medium, positive results are frequently obtained where negative results were found by the use of synthetic media. The occurrence of such bacteria at lower depths of undisturbed peat bogs can only prove that these bacteria are active in the peat in bringing about a slow and gradual decomposition of the cellulose. Some of these bacteria are being studied in further detail.

SUMMARY

1. A study has been made of the occurrence of bacteria in different layers of a number of lowmoor, sedimentary, and highmoor peat profiles.

2. The idea prevalent in some quarters that peat bogs are sterile below the surface has been shown to be entirely wrong. An abundant population consisting of bacteria and, in the case of certain lowmoor peats, of actinomyces was found at all depths of the peat profiles.

3. In the case of the highmoor peats, the sphagnum layers contain only a relatively limited bacterial population. However, below these layers, or as soon as the forest, sedge, or sedimentary layers of the peat are reached, there is a great increase in bacterial numbers.

4. The bacteria found in the lower depths of the highmoor peat profiles are autochtonous, or native to their medium, and have not been brought there by an outside agency. They find in the anaerobic system of those peats as natural a substrate as the aerobic bacteria find in soil or elsewhere, where free oxygen is admitted.

5. The fact that the greatest numbers of bacteria were found in those layers where the greatest decomposition has taken place indicates that these bacteria are largely concerned with the process of decomposition.

6. The existence of cellulose-decomposing bacteria has been established not only in lowmoor and forest peats, but also in highmoor peats. The fact that in the latter the reaction is not very favorable for the development of these organisms and the fact that the cellulose and hemicelluloses of the sphagnum plants are highly resistant to decomposition by microörganisms, account for the very slow disintegration of the sphagnum plants in the process of peat formation. This is further substantiated by the fact that, although sphagnum plants have only a relatively low nitrogen content (about 1 per cent of the dry weight), a part of this nitrogen will be liberated as ammonia when the decomposition of the sphagnum plants takes place, as a result of the inability of the microörganisms to attack readily the carbohydrates of these plants.

7. Results have been submitted which prove beyond doubt that not only are microörganisms present in peat laid down many centuries ago; not only are they found there in great abundance, but that their abundance is closely correlated with the decomposition of the peat-forming plants, as well as the gradual changes still taking place in the peat itself.

8. These results tend to prove that microörganisms, largely bacteria, are chiefly responsible for peat formation and peat transformation.

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PLATE 1

GROWTH OF ACTINOMYCES IN LOWMOOR PEAT PARTIALLY DRAINED

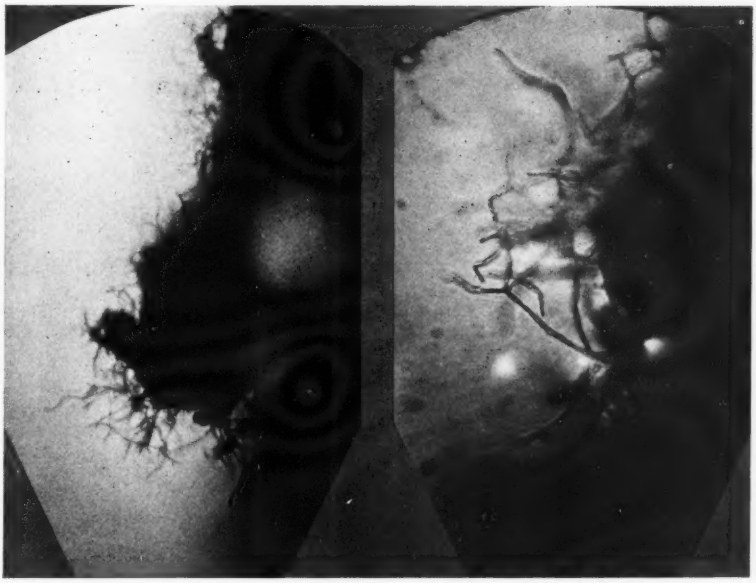


FIG. 1a

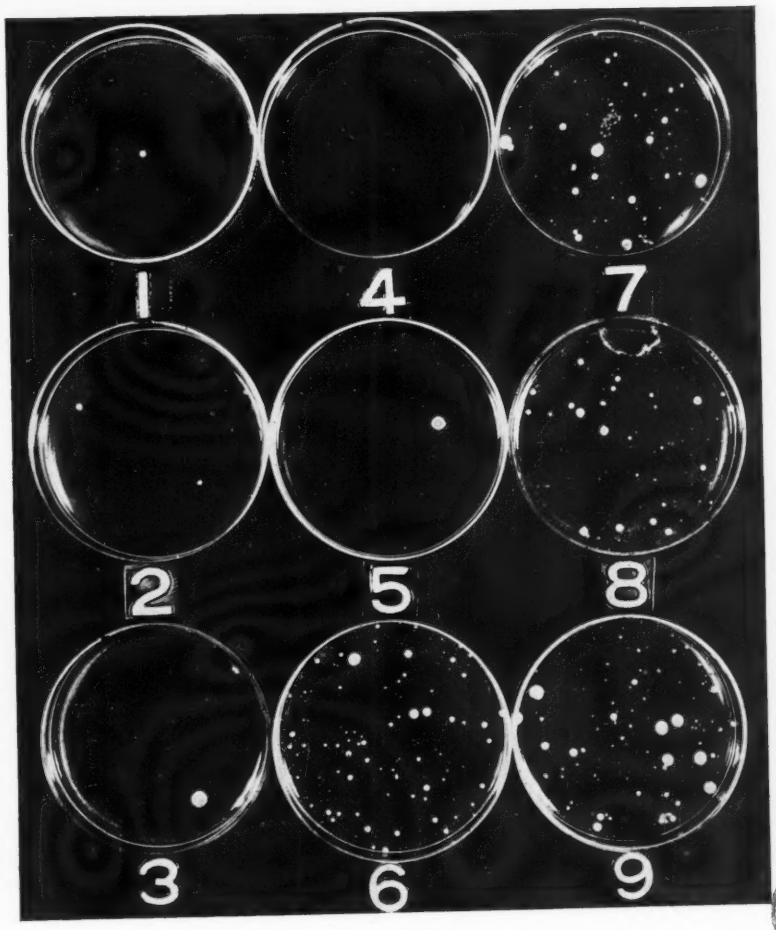
FIG. 1b

PLATE 2

DEVELOPMENT ON PLATES OF BACTERIA FROM DIFFERENT DEPTHS OF A HIGHMOOR PEAT PROFILE

Dilution in all cases, 50.000; moisture content is given in table 6; depths: 1-surface, 2–5 cm., 3–30 cm., 4–45 cm., 5–75 cm., 6–195 cm., 7–330 cm., 8–450 cm., 9–570 cm.

PLATE 2



UNIV. OF MICH.

A NEW MANOMETRIC APPARATUS FOR THE MECHANICAL ANALYSIS OF SOILS AND OTHER DISPERSE SYSTEMS

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The subject of mechanical analysis of soils has received a good deal of attention from soil workers during recent years. The modern tendency has been to express the mechanical composition of a soil in the form of a continuous curve, and many ingenious methods have been suggested for this purpose. For a description of the various methods of determining the size distribution of soil particles, the reader is referred to an excellent résumé of the subject by Odén (4), whose automatic balance (later known as the Odén-Keen balance in its improved form) is well known.

Of the more recent ones may be mentioned the hydrometer method of Bouyoucos, which consists in placing a specially made hydrometer in the soil suspension and taking readings at various intervals of time (1). The technique of the method is similar to that used by Pratolongo as far back as 1917 (5), who employed a Westfal balance instead of the hydrometer. The principle of the method was first enunciated by Wiegner (9), and depends on the variation of the density or hydrostatic pressure with the time at a definite distance from the surface in a sedimenting column.

Bouyoucos' method though attractively simple is subject to grave errors, which have been pointed out by Keen (3). These errors are avoided in the new type of hydrometer devised by the writer and described elsewhere (7). It consists of a short bulb (6–8 cm. long), and a long thin stem (50–60 cm. long), the readings being taken with a special device accurate to the fraction of a millimeter. Wiegner's original method of balancing liquids and its subsequent modifications suffer from many serious defects, the chief of which are the small variations in the height of the suspension and the measuring tube, and the sensitivity of the latter to small variations in temperature. These defects have been partly overcome by Odén by the use of a liquid of low specific gravity in the measuring tube and immersing the latter in the suspension. The experimental technique however still remains tedious.

Crowther has described an apparatus for the direct determination of summation percentage curves in mechanical analysis (2). It is based on the

[1] This work was carried out by the help of a grant from the Imperial Council of Agricultural Research, and the writer takes this opportunity of recording his indebtedness to the council. Acknowledgments are also due to the Department of Agriculture, Punjab, for the loan of apparatus and other facilities for work.

principle that the difference in hydrostatic pressure between two points separated vertically by a distance which is small compared with the total depth of the sedimenting column, may be taken without serious error as the density at a point midway between them. Although the variation in the hydrostatic pressure between such points during the sedimentation of a dilute suspension is small, it is possible to measure it by the help of a highly sensitive micromanometer. From the data given, however, it is doubtful whether the apparatus is capable of a high degree of sensitivity, for instance a 1 per cent suspension of sand is shown to give a maximum difference in the manometer of 1.2 cm., which is equal to a little more than 8 per cent of any fraction for 1 mm. difference in the manometer and as this represents actual difference in the levels of the manometric liquid, the movement of the meniscus would be only half of that. The magnification can be increased by using a suspension of higher concentration, but it is not entirely free from objection besides having its limitations. No data are given to show how far the method compares with, say, the pipette technique.

The following apparatus will be found useful for routine analysis as well as for work requiring greater precision.

DESCRIPTION OF THE APPARATUS

The apparatus shown diagrammatically in figure 1 is based on the principle of the differential liquid manometer, having a mixture of aniline and benzene (of density slightly higher than that of water) as the heavier liquid, and water itself as the lighter liquid. Two cylinders of equal diameter and fitted with ground glass stoppers, are used, one to hold the soil suspension and the other water, filled to the same height as the suspension. By the help of a three-way tap the connection between the suspension and water column can be established directly or through the manometer as desired. The lower end of the tube that dips into the suspension is spiral shaped so that if the suspension enters, it cannot rise above the level of the tip.

The suspension is well shaken and the cylinder placed alongside the one containing water. The apparatus is then lowered to the desired depth and direct connection made between the two cylinders. Since the suspension can support a higher column of water, the level in the water cylinder rises by a few millimeters depending upon the concentration of the suspension and the depth to which the end of the tube has been lowered. After about 3 minutes the tap is turned off and the apparatus taken out. If too much suspension has entered the spiral tube it is washed out by dipping the other end into a cylinder of water and syphoning it out. The aniline-benzene meniscus is also brought to the lowest point on the manometer tube adjoining the suspension cylinder. The suspension is again shaken and set aside just when a stop watch is started. Since a preliminary levelling of the liquids in the cylinders has already been effected, the connection is established through the manometer. At first there is a slight depression of the meniscus in the tube by the side of the suspension,

which soon begins to rise, and steadily moves up as the particles settle down and its level is noted at suitable intervals of time as explained subsequently either directly by a scale attached to the manometer tube or by the help of a kathetometer.

If D is the internal diameter of the cylinders and d of the manometer tube, the magnification is D^2/d^2. For a 1 per cent suspension which has a density of 1.0063, the level of the water will be $0.0063v$ cm. higher than that of the

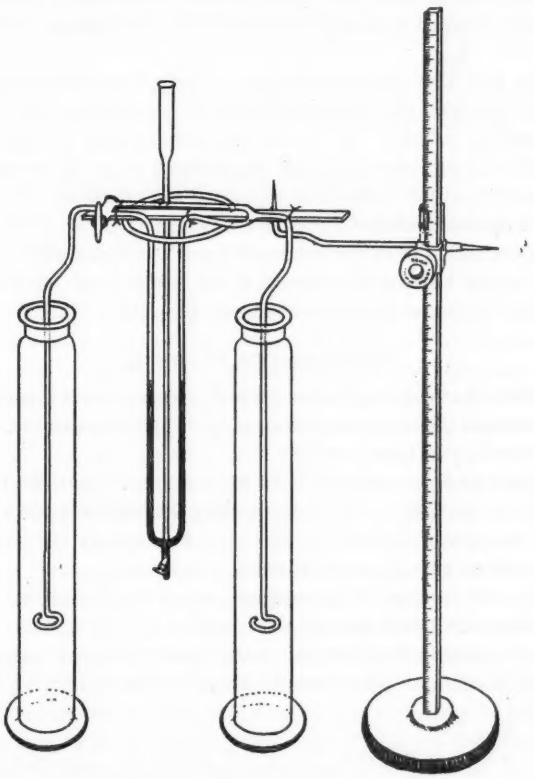

FIG. 1. DIAGRAM OF THE MANOMETRIC APPARATUS FOR THE MECHANICAL ANALYSIS OF SOILS

suspension when the side tube is dipping v cm. below the surface of the suspension. To produce this difference, however, when both the cylinders are connected, the fall in the suspension level and the corresponding rise in the water level must be equal to $0.0063/2$ cm.; and, vice versa, the same rise and fall must take place in the opposite direction when the whole of the suspension settles down. However, this change in the levels of the cylinders will correspond to a movement of the meniscus in the manometer of D^2/d^2 0.0063 $v/2$

cm. or when 1 per cent of the total solids in the suspension falls down the manometer will register a change of $D/d \times 0.0063\ v/2 \times 100 = a$ cm. In other words the percentage of any fraction settled down between times t and t' from the beginning of sedimentation will be obtained by dividing the change in the meniscus reading during the above time interval by a. As long as the sedimentation cylinders used are of the same diameter, a remains constant. If a 2 per cent suspension is used then obviously the change in the manometer readings must be divided by $2a$ and so on. Similarly if the depth of the sedimentation column is altered from v to v' the readings are to be divided by av'/v.

It will be seen that the magnification of the instrument depends upon the size of the cylinders, the concentration of the suspension, and the depth of the sedimenting column. By a judicious combination of these the desired magnification to suit any particular requirement might be obtained. In the writer's instrument the manometer registered a total change of 33.3 cm. for a 2 per cent suspension when the side tube was kept at 30 cm. depth, or a change of 3.3 mm. corresponded to the settling of 1 per cent of particles. The manometer tube had an internal diameter of about 6 mm. and the cylinders were about 10 cm. in diameter and about 45 cm. in height.

INTERPRETATION OF RESULTS

The method of calculating the results is the same as for Wiegner's apparatus, the mathematical treatment of which is given in Odén's paper (4). The following exposition may be found simpler.

Supposing a uniform suspension of soil consists of particles of equivalent diameter $d_1, d_2, d_3, d_4, d_5 \ldots\ldots$ and supposing the concentration of the various groups of particles is $A, B, C, D, E \ldots\ldots$ respectively and the time taken by each individual group to settle 10 cm. is $t_1, t_2, t_3, t_4, t_5 \ldots\ldots$

If the side tube is dipped in the suspension to a depth of 10 cm. and readings of the meniscus are taken after time intervals of $t_1, t_2, t_3, t_4, t_5 \ldots\ldots$ from the beginning of sedimentation, then the change in the meniscus during the various time intervals will have been brought about by the settling of the particles as follows:

(a) $$A + B \times \frac{t_1}{t_2} + C \times \frac{t_1}{t_3} + D \times \frac{t_1}{t_4} + E \times \frac{t_1}{t_5} \ldots\ldots \text{after time } t_1$$

(b) $$A + B + C \times \frac{t_2}{t_3} + D \times \frac{t_2}{t_4} + E \times \frac{t_2}{t_5} \ldots\ldots\ldots \text{after time } t_2$$

(c) $$A + B + C + D \times \frac{t_3}{t_4} + E \times \frac{t_3}{t_5} \ldots\ldots\ldots\ldots \text{after time } t_3$$

(d) $$A + B + C + D + E \times \frac{t_4}{t_5} \ldots\ldots\ldots\ldots\ldots \text{after time } t_4$$

(e) $$A + B + C + D + E \ldots\ldots\ldots\ldots\ldots\ldots \text{after time } t_5$$

Or the change in the meniscus, say, during the time interval between t_4 and t_5 has been brought about by the settling of $E\left(1 - \frac{t_4}{t_5}\right)$ fraction of particles of diameter d_5. Or the percentage of particles of diameter d_5 is simply determined by dividing the change in the meniscus reading between times t_4 and t_5 by $\left(1 - \frac{t_4}{t_5}\right)$. Similarly the meniscus changes due to the settling of other particles are computed. Since the total change in the meniscus reading due to the settling of the whole suspension is known, the percentage of any fraction is easily calculated.

Times t_1, t_2, etc. corresponding to diameters d_1, d_2, etc. are calculated from Stokes' law or may be taken from the table given by Puri and Amin (8).

DIRECTIONS FOR FILLING THE INSTRUMENT

The density of aniline-benzene mixture is adjusted by the help of a hydrometer. This approximately corresponds to 4 parts of aniline and 1 part of benzene. About 500 cc. is prepared and stored for use. It is to be remembered, however, that since aniline-benzene mixture has a coefficient of expansion higher than that of water, the density should be adjusted whenever there is an appreciable rise or fall in the working temperature, especially the former.

The apparatus is thoroughly cleaned with H_2SO_4-chromic mixture before filling. This is done best by filling the manometer through the middle vertical tube with the cleaning mixture and leaving overnight. Next day, after thorough washing, the instrument is filled with water to which just enough NaOH has been added to make it alkaline to phenolphthalein. The vertical tube is then filled with the aniline-benzene mixture through the cup. The side tubes are then put into two cylinders filled with water to the same level and connected through the manometer by gently opening the tap connecting the vertical tube with the manometer. When the appropriate amount of the mixture has been let in some mercury is poured into the vertical tube, and by again opening the tap gently it is allowed to rise about a centimeter above the tap. This mercury seal is necessary, as otherwise the aniline-benzene mixture dissolves the tap grease and slowly creeps out. The actual time taken in filling after cleaning the instrument is not more than 10–15 minutes.

The meniscus in the manometer should move up and down freely with an even convex curvature. If any tendency to stick or flatten at the interface is noticed, it is an indication that the instrument has not been cleaned properly. Sometimes the aniline-benzene thread breaks or shows a tendency to break, in that case the whole of it is swept out by dipping one of the side tubes into a cylinder containing alkaline water and syphoning. Mercury is then poured out. Bubbles of air that collect in the spiral tubes as a result of the pushing out of mercury are removed by syphoning out water and refilling the manometer as before. This emptying and refilling takes only 5 minutes at the most.

The cylinders should be kept over a stone bench. Slight variations of temperature as long as they affect the two cylinders equally do not matter, but if one side faces a window, or the room is draughty, the results might be affected, in which case the cylinders might be kept in bottomless wood cases or immersed in a tank of water.

EXPERIMENTAL

Fifty grams of soil were treated by the NaCl-NaOH method of dispersion described by the author elsewhere (6), made up to 2,500 cc. (2 per cent suspension), and transferred to the sendimenting cylinder. Into another cylinder, 2,500 cc. of water having the same temperature as the suspension was poured and the two were kept side by side. Immersing the instrument to 30 cm.

TABLE 1

Mechanical analysis of two soils by the manometric and pipette method

DIAMETER OF PARTICLES	SUMMATION PERCENTAGES			
	P.C. 7		P.C. 2	
	Pipette	Manometric	Pipette	Manometric
mm.				
0.06	83.6	85.5	89.6	....
0.05	....	79.2	....	91.5
0.04	71.4	71.5	86.5	89.6
0.03	....	63.0	....	86.2
0.02	54.2	52.8	78.4	81.7
0.01	38.6	38.2	70.2	71.9
0.008	35.3	34.0	67.8	68.6
0.006	31.4	30.2	65.1	65.2
0.005	....	27.8	....	62.3
0.004	26.6	25.9	62.2	62.2
0.002	21.8	22.9	59.3	59.4

depth enabled the first reading to be taken when all particles larger than 0.05 mm. diameter had settled down. Further readings were taken at suitable intervals of time corresponding to other diameters according to the working temperature. For this purpose the table of settling velocities at different temperatures given by Puri and Amin is used (8). After the larger particles, say up to 0.01 mm. diameter, have been determined, the suspension is shaken again and the instrument let down to a depth of 15 or 10 cm.; this reduces the time intervals to one-half or one-third respectively, with a corresponding decrease in magnification.

When the suspension has been settling for a few hours and it is necessary to find the percentage of particles left in it, the instrument is gently raised, after the two-way tap has been closed, by 1 or 2 cm., and the change in the manometer noted after the connection has been established again.

Since

$$D^2/d^2 \times (S - 1)\, v/200 = a$$

where S is the density of the suspension, if now the instrument is raised by 1 cm. we have

$$D^2/d^2 \times (S - 1)(v - 1)/200 = a'$$

and the change in the manometer reading being $a - a'$, we have

$$a - a' = D^2/d^2 \left(\frac{(S - 1)\, v - (S - 1)\, (v - 1)}{200} \right)$$

$$= D^2/d^2\, (S - 1)/200$$

From this equation S can be calculated, and being proportional to the concentration, the latter is easily known. In practice the relation between $a - a'$ and S, or rather concentration of suspension, is worked out once for all as a part of the calibration of the instrument.

In table 1 are recorded the results of mechanical analysis of two soils P. C. 7 and P. C. 2 by both the manometric method and the pipette method using 2 per cent suspension in every case. As will be seen, the agreement is quite good.

SUMMARY

A manometric apparatus for the mechanical analysis of soils is described. It is based on the principle of the differential liquid manometer, having a mixture of aniline and benzene (of density slightly greater than water) as the heavier liquid and water itself as the lighter liquid.

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LYSIMETER STUDIES: I. MOISTURE PERCOLATION THROUGH THE SOIL PROFILE[1]

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The movement of moisture through the soil under natural conditions has not been studied to any extent because of the difficulties involved in retaining the undisturbed state of the soil mass during the process of experimentation. Most of the studies on the movement of the accepted conventional forms of water—gravitational, capillary, and vapor—were made on soil material. Green (6) justly remarks that in order to get a true picture of the moisture properties of the soil, a technique has to "be developed for measuring the soil characteristics *in situ;* until then laboratory experiments will deal not with soils, but with soil materials."

REMARKS ON LYSIMETER STUDIES

An approach to the study of the movement of moisture under natural conditions was attempted as early as the end of the eighteenth century by the introduction of the so-called drain-gauges, later known as lysimeters. Dalton's[2] original idea was to follow up the fate of the natural precipitation with reference to the feeding of ground waters which nourish the streams. One of the fundamental questions was then to find out how much of the precipitation percolates through the soil. Gradually the lysimeter method was adopted in studies of soils as such and the percolation or movement of moisture became a matter of secondary consideration. Analyses of the leachings in relation to the ammonia, sulfur, and other constituents lost from the soil and those brought down by the rain water became the primary purpose of lysimeter studies. Later and in recent years lysimeters have been also utilized for the study of the losses of fertilizer ingredients and soil amendments under cropped and fallow conditions. Moisture losses were of course considered in this connection.

And now, after close to 150 years of work with lysimeters, we are still in doubt about the nature of the movement and percolation of water through the soil—the phenomenon which was the fundamental cause of the origin of lysimeters. Lysimeters are still open to the serious criticism, which has been

[1] Journal Series paper of the New Jersey Agricultural Experiment Station, department of soil chemistry and bacteriology.

[2] Dalton the famous English scholar, the father of the atomic theory, is credited with being the first one to install lysimeters. A more detailed discussion of the origin, history, and development of lysimeters is now in the process of preparation.

recognized ever since the early days of lysimeter studies, namely, that the findings do not represent the true conditions of the soil; they are true for the *one or the other soil material prepared and arranged in a particular way.* And there are countless ways of preparing and arranging the soil material and each arrangement will give a different answer—or at most not all of them will give the same answer—to the problem under consideration. For there is only one way in which the soil will respond as a soil and that is when it is not disturbed. Only then may one study its behavior and reactions, when its natural arrangement, its constitution, which has formed in the course of ages, its structure, and its make-up are still preserved and in place.

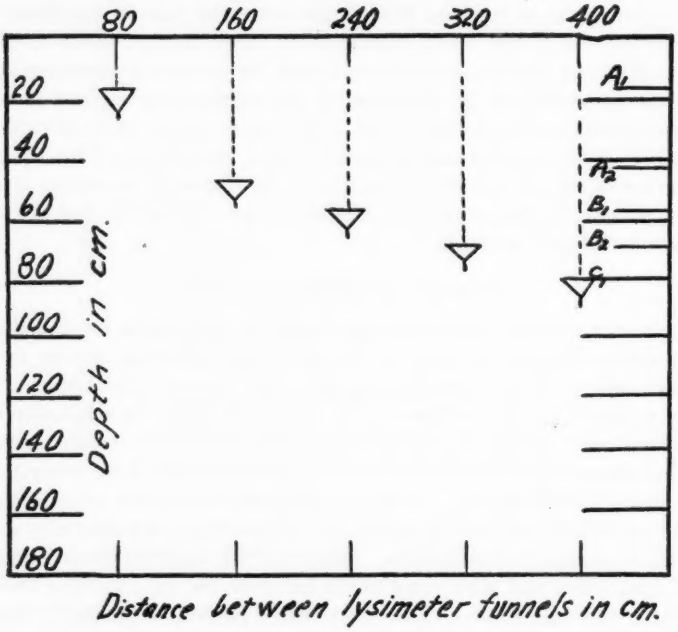

FIG. 1. DIAGRAMMATIC SKETCH OF LYSIMETERS UNDER RESPECTIVE HORIZONS

No botanist would study plant reactions with respect to the behavior of the plant as a whole by macerating the plan. And it is just the thing we are doing when we dig up the soil body, remove stones, sieve the material, and dump it into lysimeter tanks. By this method not a single element of the natural conditions of the soil body is preserved, save the rainfall; and even this natural factor is frequently interfered with. It is known that artificial watering of the lysimeters is sometimes resorted to. In some lysimeters the rims are arranged to prevent surface run-off—another abnormal condition.

Anyone familiar with the fundamentals of the genetic school of soil science appreciates what it means to take out the soil material foot by foot, mix it,

and place it into a tank in the "same order." Actually it means to upset the established conditions, mix some of the material from the horizon of illuviation with that of the horizon of eluviation. This of course will introduce an entirely new set of physical, chemical, and biological reactions, since each of the horizons maintains a definite set of these reactions true to itself and not true for any other horizon. It is, for instance, very probable that in the Cornell Agricultural Experiment Station lysimeters (11, 12) the first foot of soil placed on top contained the surface of the B_1 horizon. The data (11, p. 11) on the mechanical composition of the soil used in these lysimeters show that the first foot contained 22.63 per cent of clay, the second foot—32.72 per cent, the third foot—38.62 per cent, and the fourth foot—36.67 per cent. It is apparent that the second foot of the soil, with 50 per cent more clay than in the first foot, represents the B horizon which extends apparently through the entire or a part of the third foot. Under such conditions some of the colloidal substances from B_1 would tend to produce a compact, impervious layer close to the surface and prevent the percolation of the rain water. Very few of the inherent soil forming elements and reactions of the A horizon, such as porosity, texture, structure, organic matter content, and aeration could behave normally. It is therefore no wonder that in the uncropped lysimeters of the Cornell experiment station the soil *"became so compact that at the end of ten years, drainage was poor and water frequently stood on the surface for considerable periods,"*[3] (12, p. 6). Of course, cropping the soil will tend to break up the surface compact layer and the introduction of the organic matter will bring into play the eluviation reactions and hence improve the leaching capacity of the soil material.

The aforesaid might also explain the "peculiar" behavior of the tanks with respect to the nitrogen balance (12, p. 38):

> In 1914 the nitrogen showed a tendency to fall below its usual ratio to the flow of drainage water. It is difficult to trace this to any weather conditions obtaining that year, as neither the rainfall nor the temperature was abnormal during the months when nitrate formation might be expected to be active. It is possible that with the settling of the soil in the tanks and the diminished aeration, there is a tendency for the process of nitrate formation to be less active.

In the lysimeters of the Geneva station (New York State Agricultural Experiment Station) the soil material was placed into the tanks in a somewhat different order from that in the Cornell lysimeters.

> The bottom 2 feet of the 4-foot tanks received soil from the 16–36 inch depth. The second foot received soil from the 8–16 inch depth, while the surface 8 or 9 inches received soil from the 0–8 inch depth.

The soil material is of a lighter texture than the soil in the Cornell lysimeters.

[3] Italics are mine.

Still in the Cornell lysimeters 78 to 82 per cent[4] of the total rainfall percolated through the unplanted tanks and 54 to 62 per cent through the planted tanks, and the Geneva lysimeters lost only 40 per cent of the total rainfall from the fallow tanks and 21 per cent from the planted tanks. Thus the Geneva figures are only about one-half those of the cornell lysimeters. And still the total rainfall and the temperature are about the same in the two localities. Collison and Mensching (1) from the Geneva station find it difficult to explain such great discrepancy. It is the opinion of the author that the abnormality may be laid to the abnormal conditions of arranging the soil material in the tanks.

In the Tennessee lysimeters, Mooers (17) filled his tanks by following the Cornell (11) method, except that the surface 6 inches came from the plowed layer. Each layer "after being carefully mixed was laid down in the same order in the can as it was removed from the field." The tanks are $\frac{1}{5,000}$ of an acre; there are tanks of various depths, from 6 feet to 1 foot, the latter having only 9 inches of (surface ?) soil material.

MacIntire (13), also from Tennessee, installed another set of tanks embracing an area of $\frac{1}{2000}$ of an acre. Two depths were used: 12 inches and 24 inches. The soil

> was thoroughly screened through a ¼-inch sieve, carefully mixed and closely covered during the overnight period required for the making of moisture determinations, and during the mixing of the soil and the materials. One hundred pounds of moisture-free surface loam soil representing a depth of approximately 8 inches was used for each tank.

In the 2-foot tanks the surface 8 inches was underlaid with a foot of clay subsoil. Thus these lysimeter tanks differed somewhat from Mooers' inasmuch as they contained soil material from below the plowed layer, which is usually not more than 5 to 6 inches deep. From the data presented by MacIntire (14, p. 383) on the leachings of six tanks without and six tanks with a subsoil and the rainfall data of the meteorological station at Knoxville, in the vicinity of which the lysimeters are located, it has been calculated that over a 4-year period the average amount leached was about 44 per cent of the total rainfall. And these were *uncropped tanks* but treated with lime. Two-year data presented by Mooers (18, p. 131) on the leachings from 4-foot lysimeters on three soil series show about the same (43.12, 50.86, and 42.50 per cent respectively for the three series of soils) per cent of leachings. *And the 4-foot tanks were cropped*, a condition which as a rule cuts down the percolation of moisture.

Why both types of lysimeter tanks at Tennessee should percolate practically the same amount of leachings and incidentally be about equal to the amount

[4] In the recent publication from Cornell (12) the figure for the fallow tanks is 66 per cent. The discrepancy is due to the peculiar method of averaging the results of the fallow tanks. The original fallow tanks were cropped after the first 10 years and other tanks which were cropped until then were fallowed for 5 years and the leachings from these were averaged with those from the original fallow tanks. These "newly" fallowed tanks percolated less water and in that way the average was reduced from 82 to 66 per cent.

leached from the Geneva lysimeters is a matter of conjecture. The climatic conditions in the two localities vary considerably; the soil material used, the depths from which it was dug, and the way it was placed in the lysimeter tanks in the two stations, all were different. The only equality factor in the two sets of lysimeters is the abnormal condition of the soil as such, i.e, there is no soil body in either of the lysimeters. Another similarity might be found in the fact that the surface soil material was probably from the A horizon. Some abnormalities about lysimeters have been recognized by those responsible for installation. Thus Mooers (19, p. 10) states:

> The data from the cylinder experiments, as published in Bulletin 118, show that soils placed in galvanized iron cylinders and lysimeters and exposed to the weather, behaved in a decidedly abnormal manner as compared with soils in the field.

The source of these abnormalities was not sought in the make-up of the soil body which was destroyed by "carefully mixing" the soil material as it was dug out from the field. Some other external factors were made responsible, one of which was the "lack of run-off caused by the projection of the rims for two or three inches above the soil."

In view of the aforesaid, the type of lysimeters used at Cornell, Geneva, Tennessee, and other experiment stations and agricultural institutions is not suitable for the study of the movement of moisture through the soil. The data obtained from the leachings of such lysimeters cannot be applied to interpret phenomena and reactions that might occur under natural conditions in the field. What one might expect from lysimeters placed in the soil body will be shown in the following data; but before these data are presented a review will be made of a note by Mooers and MacIntire (20) in which an argument is raised about the author's claim (17) that "the only rational method of studying the drainage of each horizon is to install a series of lysimeters at the depths of the respective horizons without disturbing the natural position of the soil profile." They claim that "if this unqualified statement be true it means that during the past twenty years *the properties of the several profiles of different soils*[5] have been studied by an irrational method at the Tennessee Station, and with three types of equipment."

An examination of the many papers published by Mooers and MacIntire and associates revealed no lysimeter studies involving "*the properties of the several profiles of different soils.*" From the publications mentioned it is clear that the lysimeters installed in Tennessee were filled with soil material with no regard to the profile constitution of the soil body. It is thus apparent that as far as the study of the soil as such is concerned *the method used is irrational.*

Another point raised by Mooers and MacIntire is that "homogeneity in the soil mass is the paramount essential in lysimeter experiments." This phase has been dealt with by MacIntire elsewhere (15), but from neither one of the publications is it clear just what is meant by "homogeneity in the soil mass."

[5] Italics are mine.

It is generally understood that the soil is not a homogeneous system, which by the definition, as applied in the "Phase Rule" (4), is one "which is uniform throughout its whole extent and possesses in every part identical physical properties and chemical composition." And it is therefore also puzzling why Mooers and MacIntire (20) attributed to the writer the thought that "homogeneity is hoped for or assumed" in the new type of lysimeters installed at the New Jersey Agricultural Experiment Station. On the contrary, from the genetic point of view in soil science the soil as an independent natural body with a clear-cut separation of horizons in the profile[6] is a heterogeneous system which, by definition (4), "consists of parts which have different physical properties, perhaps also different chemical properties, and which are marked off and separated from one another by bounding surfaces." Although this definition as applied in the "Phase Rule" may not at present be applicable in its entirety to the soil system, it approaches it and with the broadening out of the physico-chemical principles it might in time be applied fully. At any rate the principle of homogeneity is ruled out from the soil system.

The argument raised by Mooers and MacIntire (20) that "the value of the lysimeter is that it serves as a means of establishing fundamental principles that relate to cultivated soils and their subsoils" is not convincing. For after all, cultivated soils are nothing more than natural soils in which the upper 5 to 6 inches (in some cases slightly deeper) are disturbed. Beyond these 5 to 6 inches, which as a rule are a part of the horizon of eluviation, the soil body remains undisturbed and influences the behavior of the overlying cultivated soil material. To take this material from a depth of 5 to 6 inches, confine it into a cylinder, and make it 9 inches deep or more, means the introduction of a new set of conditions: moisture, temperature, and pressure relationships change and with them other physical, chemical, and even biological properties change.

The question raised by Mooers and MacIntire (20) about the perpendicular movement of moisture in the soil is, from the data obtained by the new type of lysimeters, answered in the negative. No claim has been made by the author that the direction of the gravitational water is perpendicular, as might be implied from the statement by Mooers and MacIntire. Just because moisture does not move exclusively in a perpendicular direction, there is more reason to criticize the filled-in type of lysimeters which force the rainfall to follow a perpendicular direction.

The underlying motive for the installation of lysimeter equipment is the study of the drainage, which in turn might tell us about the movement and translocation of the soil and plant-food constituents which are formed in the soil profile or which are added naturally by the humus-accumulative Ao layer or through the addition of fertilizers in the cultivated soils. And for this reason the method with the filled-in type of lysimeters is irrational and the findings from such data cannot be applied to soil conditions. The leachings from such

[6] In a mature soil the morphological, chemical, and physical characters are distinct; in an immature soil the chemical and physical properties differentiate the horizons in the profile.

lysimeters give no picture of what is going on in the soil, for they do not contain the heterogeneous soil body. They might give an inkling about some reactions that take place in the soil material under this and no other condition and, by the way, each one of such strictly controlled conditions has many uncontrollable factors—amd will not hold true with the slightest change made.

Most of the data obtained with the filled-in type of lysimeters could just as well be procured by conducting similar experiments in drainage pots under controlled conditions in the greenhouse and in the laboratory. As long as the fundamental requirement of having the soil in a natural state cannot be satisfied by the filled-in type of lysimeter, there is no point in preferring an out-of-door elaborate and expensive system of drainage tanks to one in the greenhouse. There is the remote possibility of utilizing the filled-in type of lysimeters for the study of soil formation. In the course of time the soil material in the tanks will undergo changes due to the activity of the soil formers. A soil body with a differentiation of horizons will be created. But it seems that it would be a rather long drawn out experiment and, besides, we have at our disposal simpler and well-proved methods for the study of soil formation.

The criticism and analysis advanced against the filled-in type of lysimeters of the Tennessee, New York, and Cornell experiment stations apply as well to others. To overcome some of the cardinal objections raised, a new type of lysimeter has been installed at the New Jersey Agricultural Experiment Station. It was realized at the outset that in connection with this new type of lysimeter we must take into consideration the uncertainty about the true quantitative factor with regard to the percolation, of which more will be said in the course of presenting the data for the first 2 years. Other minor factors which might introduce some complications in applying the data of the leachings to actual natural conditions in the soil will also be brought out. On the whole, however, the data obtained give very striking and illustrative information as to the movement and translocation of the moisture and the substances carried in it through the soil profile.

NEW TYPE OF LYSIMETERS

A pit is dug 120 cm. wide, 180 cm. deep—depending on the profile depth of the soil studied—and 460 to 500 cm. long. Under each horizon a tunnel, 50 cm. long, is dug in the shape of the lysimeter which consists of a shallow funnel made of block tin 30.6 cm. in diameter ($\frac{1}{55,000}$ of an acre in area), 4 to 5 cm. deep, with a sharp edge 3 to 4 mm. high, and with nine to ten 2-mm. perforations in the neck. This funnel is filled with quartz pebbles and its sharp edge rests against the roof of the tunnel. When the funnel is placed in the tunnel the distance from the wall of the pit to the funnel is 20 cm. The funnel is wedged upward and the open space between it and the wall of the pit is filled with the soil material dug out from the tunnel. After all the funnels are placed under the respective horizons—80 cm. apart on a horizontal line as

shown diagrammatically in figure 1—a board wall is built 8 to 10 cm. away from the soil wall and the space is filled in with soil. Reinforcing and bracing the studdings to which the wall boards are nailed is an important precaution against their collapsing under the weight of the filled in soil.

Each funnel is connected by means of a coupling with a block tin tube 6 mm. in internal diameter. The tube leads to a receptacle for the leachings. Figure 1 gives the front view of the wall with the lysimeter funnels in place under the respective horizons.

The pit is covered with a shed roof extending just a few centimeters above the ground. A gutter leads the water off to a distance away from the area where the lysimeters are located.

Plate 1, figure 1, gives a general view of the location of the lysimeter pit and its general external appearance and surroundings. Figures 2 and 3 of plate 1 show the interior of the lysimeter pit. Attention is called to the fact that the points where the tubes come out from the walls—as shown by the tape and letters—do not indicate the exact position of the funnels. The tubes were bent downward and the angle was not the same for all the funnels.

The new type of lysimeter is rather old. Gemmerling (5) designed his after the pattern of Ebermayer (2, 3), who used this type of lysimeter in studies on the moisture relationships in the forests. In his studies on the methods of investigating soil moisture, Popov (21) also used this type alongside a removable type.

A virgin forest soil mapped by the Soil Survey as Sassafras sandy loam was selected. Morphologically this soil shows feeble signs of podzolization, except perhaps some specks of SiO_2 in the A_2 horizon, which has a slightly lighter grayish brown tinge than the overlying A_1. The depth of the respective horizons as determined by the standard methods of profile study is indicated on the diagram. Chemically[7] this soil shows distinct podzolization and is to be classified as a podzolic, or slightly podzolized soil, a subgroup of the large zonal type—the podzols.

The tree vegetation[8] on the lysimeter plot consists of: black locust (*Rubinia pseudo-acacia* L.), flowering dogwood (*Cornus Florida* L.), sassafras (*Sassafras variifolium* [Salisb.] Kuntze), white oak (*Quercus* sp.), black oak (*Quercus* sp.), red maple (*Acer rubrum* L.), shag-bark hickory (*Carya ovata* [Mill.] K. Koch), and sweet cherry (*Prunus avium* L.). The trees are listed in the approximate order of abundance.

One property of the soil on the plot must be mentioned at this time, namely, the moisture content. The material was sampled just when the lysimeters were installed and the soil seemed to have been approximately in its optimum moisture condition. The figures given are on the basis of the volume-weight

[7] A complete chemical analysis of soil by horizons will be presented in the next paper of this series.

[8] For this information the author is indebted to Dr. C. W. Watson, National Research Fellow at the New Jersey experiment station.

of the soil. A_1 contained 30.23 per cent moisture, A_2—24.26 per cent, B_1—27.8 per cent, B_2—16.7 per cent, and C_1—15.2 per cent.

SAMPLING AND ANALYZING LEACHINGS

The leachings, if there are any, of each horizon are being collected after each rain. Each leaching is measured; conductivity—by the Kohlrausch method—and pH—by the colorimetric method—are determined soon after it is brought to the laboratory. An aliquot is taken for analysis of dry matter, organic matter, and mineral constituents. Another aliquot is taken for total nitrogen. In addition, nitrates, sulfates, and chlorides are determined on separate aliquots.

The analyses mentioned are made whenever there are enough leachings. Otherwise the conductivity, pH, nitrates, sulfates, and chlorides only are determined.

LYSIMETER LEACHINGS FOR THE FIRST 2 YEARS

A_1 horizon

The lysimeters were installed in the middle of June, 1929, and the first leachings appeared June 22. The data on the leachings that percolated through the A_1 horizon for the two leaching years (the year is figured from June 22, the date when the first leachings appeared) are presented in table 1.

It will be noted that during the year 1929–30 with 37.26 inches of total rainfall 21.00 liters of leachings were collected from the lysimeter funnel under A_1, whereas during the year 1930–31 with 34.14 inches of rainfall 29.223 liters were collected. If we calculate[9] the leachings on the acre basis we find that in 1929–30 out of the 135,253.8 cubic feet of total precipitation only 40,771.5 cubic feet percolated through the A_1 horizon, a depth of 18 cm.—about 7.5 inches—or 30.14 per cent. In 1930–31, out of a total of 123,928.2 cubic feet of precipitation 56,736.5 cubic feet, or 45.7 per cent, percolated through the A_1 horizon. Thus 50 per cent more—the difference between 30.14 and 45.7 per cent—of the total rainfall percolated through A_1 in 1930–31 than in 1929–30. Actually, however, only 39.1 per cent—the difference between 21.0 liters in 1929–1930 and 29.223 liters in 1930–31—more water percolated. And yet the total rainfall for 1930–31 was 9.1 per cent lower than in 1929–30. Apparently the amount of percolation does not depend altogether on the total rainfall, but also on some other conditions. What these are has not been as yet fully established.

[9] The calculation is made as follows: The total leachings for the year are converted into cubic feet by multiplying the number of liters by 0.0353—the factor for conversion of liters into cubic feet. To obtain the total leachings on the acre basis, the cubic feet per lysimeter are multiplied by 55,000, the area of the lysimeter funnel being $\frac{1}{55000}$ of an acre. To get the total rainfall on an acre basis the area of an acre—43,560 square feet—is multiplied by $\frac{1}{1\frac{1}{2}}$ (an acre inch) and then by the number of inches of rainfall for the year.

From observations for the 2 years and from theoretical considerations, it has been inferred that the state of the colloidal complexes in the soil to a certain extent controls the rate of percolation.

Capillary and non-capillary pore space.—When the soil is subjected to a prolonged drought the colloids—the inorganic and organic, especially the latter—lose their water of hydration, dry, and shrink. The individual textural units become cemented into structural units, decreasing thereby the capillary pore space and increasing the non-capillary pore space. And it is the latter that facilitates percolation. When, however, the soil becomes saturated the colloids imbibe water, become hydrated, and swell. A disintegration of the structural units, or, as it is sometimes called, "slaking," takes place and the result is an increase in capillary pore space and decrease in non-capillary pore space. This process hinders percolation.

Observations on the rate of percolation through the A_1 (the same holds true also for A_2 and the other horizons) horizon for the 2 years of lysimeter investigations have invariably proved that after prolonged droughts more leachings came through with relatively low amounts of rainfall, whereas during periods of moist conditions of the soil the amount of leachings was low even with a relatively high rainfall. An analysis of the rainfall data presented in table 2 in correlation with the data on the leachings as given in table 1 will illustrate the aforesaid.

After the heavy rain of 1.71 inches on June 21, which was preceded by a spell of hot weather, 1,065 cc. of leachings came through the A_1 horizon. This was followed by 0.92 inch of rainfall on June 22, which yielded 510 cc. of leachings. After that it rained almost daily up to July 3, followed by 2 rainless days, and continued with intermittent rainy and rainless (more rainy) days up to July 14. During this period the soil was in a moist condition. The data in table 1 show that after the leachings from the rain of June 23 (0.92 inch) none came through even after such heavy rains as during July 5 and 6 (0.99 inch) and July 14 (0.69 inch). It is reasonable to assume that during this rainy period the non-capillary pore space decreased as a result of the hydration and swelling of the colloids. However, the 2 weeks of drought after July 14 changed the condition of the colloids in the reverse direction and the relatively low rainfall (0.66 inch) on July 29 and 30 yielded 1,400 cc. of leachings, almost three times as much as on June 24 after a rainfall of 0.92 inch—almost a third more than on July 29 and 30.

Two other striking examples illustrating the effect of drying on the rate of percolation may be found in the data on the rainfall for July, August, and October, 1930. From July 25 to August 23, a period of 3 weeks, a severe drought prevailed. The soil in the open fields adjacent to the woods where the lysimeters are located cracked, forming large structural aggregates. As a result of that the soil was very porous and the relatively small rain (0.44 inch) on August 15 yielded some leachings—80 cc. Again, in October, after a prolonged drought a rainfall of 0.65 inch on October 15 yielded 325 cc.

and, after the drought, toward the end of the month a rainfall of only 0.37 inch on October 29 yielded 608 cc.

Another element to consider in connection with the rate of percolation is the electrolyte content of the leachings. A high electrolyte content favors the coagulation of the colloids, which in turn decreases the capillary pore space. From data on hand, which will be published in the next paper of this series, it is evident that during the period of tree defoliation—usually in October and November—the electrolyte content of the leachings, as determined by conductivity measurements and actual analysis, is at its peak and, of course, the state of the colloids is affected.

Significance of effective precipitation.—The effective precipitation—the rainfall after which leachings appear—is one of the apparent and quantitatively measurable factors in the complex relationships between the rainfall and percolation. From the columns on the effective precipitation and the other data in table 1, it is evident that this apparent factor is independent of the total rainfall. During the first lysimeter year (1929–30) with a total precipitation of 37.26 inches there were 22.47 inches of effective precipitation. During the second year, with a lower total precipitation—34.14 inches, there was a higher effective precipitation—24.81 inches. Moreover, the data show that the higher the effective precipitation the higher is the percolation through the horizon under discussion. It is important to note that the amount of leachings is directly related to the effective precipitation, but the ratio differs for the different years. For the year 1929–30 the ratio of effective precipitation to leachings is 1.07 and for 1930–31 it is 0.849. Neither are the ratios of effective precipitation to total rainfall the same. For 1929–30 the ratio is 0.603 and for 1930–31 it is 0.726.

The lack of correlation between the total and effective precipitation is also brought out in table 1 in the columns on effective precipitation, per cent of total. The inequalities noted—lack of correlation between effective precipitation and total leachings and total precipitation—are undoubtedly due to the differential behavior of the soil colloids as outlined.

Relation of temperature to percolation.—That the mean monthly temperature *per se* is not a factor in the rate of percolation may be inferred from the data in table 1. For the 2 years under consideration the total accumulated temperatures were almost exactly the same and there were very small differences between respective months during these 2 years, and yet it is unquestionable that the temperature had an effect on the rate of percolation, for it is the temperature which is under some conditions responsible for the moisture relationships in the soil. It is the temperature in the intervals between rains that controls evaporation (humidity is linked up with it) and causes drying out of the soil, which in turn determines the capillary and non-capillary pore space, especially in the A_1 horizon.

Summary statement about the leachings through A_1.—The outstanding feature about the percolation of rainwater through the A_1 horizon is that notwithstand-

ing its shallowness—18 cm. deep—only 30.14 per cent of the rainfall during 1929–30 and 45.7 per cent during 1930–31 percolated. This leaves 69.86 and 54.3 per cent, respectively, for evaporation from the surface of the soil and utilization of moisture by the plant cover. No evaporation data are available and therefore there can be no estimate of the amount of moisture available

TABLE 1

Precipitation, leaching, and temperature data in connection with lysimeter studies on the A_1 horizon at a depth of 18 cm.

1929–30							1930–31						
Laboratory number of leaching	Date of collection	Effective precipitation*	Total precipitation for month	Effective precipitation, per cent of total	Leachings	Mean monthly temperature	Laboratory number of leaching	Date of collection	Effective precipitation*	Total precipitation for month	Effective precipitation, per cent of total	Leachings	Mean monthly temperature
	1929	*in.*	*in.*	*per cent*	*liters*	*°F.*		*1930*	*in.*	*in.*	*per cent*	*liters*	*°F.*
1	June 22	1.71	.....	.....	1.065	.....	16	July 10	1.46	.....	.....	1.300	.....
2	June 24	0.92	.....	.....	0.510	.....	17	July 23	1.65	4.08	76.22	1.300	75.2
3	July 30	0.66	2.94	22.45	1.400	73.7	18	Aug. 16	0.44	.....	.....	0.080	.....
4	Aug. 15	1.31	2.41	54.36	0.755	70.8	19	Aug. 24	2.26	2.88	93.74	3.350	71.8
5	Sept. 9	4.07	.....	.....	4.740	.....	20	Sept. 17	0.89	1.43	62.23	0.350	70.4
6	Sept. 18	0.91	5.59	89.08	0.470	68.0	21	Oct. 16	0.65	.....	.....	0.325	.....
7	Oct. 3	2.10	.....	.....	3.440	.....	22	Oct. 29	0.37	1.77	57.62	0.608	52.6
8	Oct. 23	1.06	4.11	76.88	0.930	53.4	23	Nov. 6	1.20	.....	.....	1.455	.....
9	Nov. 5	0.94	.....	.....	0.390	.....	24	Nov. 19	1.72	3.27	89.30	2.420	44.2
10	Nov. 20	1.05	2.21	90.04	0.135	45.0	25	Dec. 30	1.62	2.40	67.50	4.090	33.8
11	Dec. 20	1.35	2.93	46.07	1.180	33.4		*1931*					
	1930						00	Jan.	0.00	2.24	0.00	0.000	32.2
00	Jan.	0.00	2.65	0.00	0.000	31.8	26	Feb. 19	1.95	2.37	82.27	4.100	33.8
12	Feb. 18	1.70	3.00	56.66	3.435	36.2	27	Mar. 9	1.09	.....	.....	1.770	.....
13	Mar. 11	1.34	2.31	58.00	0.250	40.5	28	Mar. 30	1.60	3.49	77.07	3.305	39.6
00	Apr.	0.00	2.18	0.00	0.000	48.2	29	Apr. 2	0.69	.....	.....	0.665	.....
14	May 17	0.90	2.54	35.43	0.100	63.6	30	Apr. 12	0.73	2.37	60.00	0.505	50.7
15	June 11	2.45	4.39	55.80	2.200	72.0	31	May 15	1.65	.....	.....	0.700	.....
...	.....	.....	.....	.....	.....	.....	32	May 24	0.68	3.24	71.99	0.475	61.4
...	.....	.....	.....	.....	.....	.....	33	June 11	2.62	.....	.....	1.950	.....
...	.....	.....	.....	.....	.....	.....	34	June 18	1.34	4.60	.....	0.475	70.4
Total for year.		22.47	37.26	.....	21.000	636.6	..	.....	....	34.14	.....	29.223	636.1

* By effective precipitation is understood the precipitation after which leachings percolated through the horizon.

to the plants. And besides, the moisture in this horizon is not the only source of water supply for the plants. A large share of the 30.14 and 45.7 per cent of rainfall that percolated through A_1 remained in A_2, as will be shown presently, and this moisture is undoubtedly available to the plants.

There is another factor to consider in the calculations made on the water

percolation through the soil under forest conditions, and that is the amount of moisture that is retained by the forest canopy. It is well known that the fine rains do not reach the forest floor, as the leaves retain much moisture. Ebermayer (3) points out that coniferous forests keep back 40 to 50 per cent of the rainfall, and hardwood—10 to 25 per cent. Of course these figures will be greater or smaller depending on the thickness of the stand and the age of the trees. How much moisture is retained by the hardwood forest cover on the plot where the lysimeters are located has not been determined. Fifteen per cent would be a rough estimate. In that case the percentage of rainfall that percolated with respect to the total precipitation that reached the forest floor would be higher than the foregoing figures.

A_2 horizon

The data on the percolation of moisture beyond the depth of the A_2 horizon—42 cm.—as given in table 3, show that through this depth the amount of percolate was greater in 1929–30 than in 1930–31. Thus in 1929–30 only 7.93 per cent of the total rainfall percolated beyond the depth of the A_2 horizon and 7.1 per cent in 1930–31. It will be remembered that the reverse was true for the A_1 horizon notwithstanding the higher total rainfall during 1929–30.

If we take the amount of leachings that reached the A_2 horizon—21.0 liters in 1929–30 and 29.223 liters in 1930–31—and calculate how much of that passed through the A_2 horizon, we find that 5.525 liters, or about 25 per cent, percolated in 1929–30 and 4.275 liters, or 14.6 per cent, in 1930–31.

An understanding of the colloidal behavior of the soil will explain the apparent contradiction. As pointed out in the discussion on the percolation of moisture through the A_1 horizon, the rate of percolation is controlled by the relative abundance of capillary and non-capillary pore space, which in turn is determined by the intermittent drying and wetting of the colloids in the soil. In this respect there is less fluctuation in the A_2 horizon because the latter does not dry out so quickly as the A_1 horizon. Still this phenomenon of drying and wetting of the colloids manifests itself in the A_2 horizon and produces the same effect as in the A_1 horizon. During the months of the latter part of August, September, and October of 1930 the soil dried out beyond the depth of the A_2 horizon and consequently the non-capillary pore space increased. The rainfall during November was not effective enough to saturate the A_2 horizon. Only in December, after the soluble salts which accumulated in the A_0 layer because of the drought and which leached from the freshly fallen dead leaves had been washed down, was a rain of 1.62 inches so effective as to give as high as 1,870 cc. of leachings from the A_2 horizon. Observations made on a nearby soil profile cut have shown that only then did the soil in the A_2 horizon become saturated and remain moist.

An examination of the data on the effective precipitation in table 3 reveals the same tendency as in the A_1 horizon: a higher leaching is indicative of a higher amount of effective precipitation. Thus in 1929–30 there were 5.525

liters of leachings with an effective precipitation of 13.38 inches and in 1930–31, 4.275 liters with 7.60 inches of effective precipitation. The ratios of effective

TABLE 2

*Rainfall data from day to day in inches**

MONTH	DAY OF MONTH															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1929																
June	....	....	....	....	....	0.13	....	0.33	....	....	....	....	....	T.	0.37	T.
July	T.	0.28	....	....	0.44	0.51	....	....	0.25	....	....	....	....	0.69	....	.....
1930																
July	0.35	0.04	T.	....	....	0.20	T.	....	T.	1.46	0.02	....	....	0.12	....	.....
August	....	....	....	....	....	....	....	....	T.	T.	....	....	....	....	0.44	T.
October	....	....	....	....	....	....	....	....	....	....	....	....	....	....	0.65	T.

MONTH	DAY OF MONTH															TOTAL
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
1929																
June	T.	....	T.	T.	1.71	T.	0.92	0.31	0.20	0.48	....	0.71	0.21	T.	....	5.37
July	....	....	0.09	....	....	T.	0.02	....	....	....	....	....	0.27	0.39	....	2.94
1930																
July	....	....	....	....	0.02	1.65	0.03	0.19	T.	....	....	....	....	....	....	4.08
August	0.01	0.17	....	....	....	....	2.26	T.	....	....	....	....	....	....	....	2.88
October	....	0.14	....	....	....	....	....	T.	....	....	....	....	0.37	T.	0.61	1.77

* The rainfall data in this table and in the others were taken from "Climatological Data," United States Department of Agriculture Weather Bureau records of the meteorological station at New Brunswick, located within 150 feet from the lysimeters.

TABLE 3

Precipitation and leaching data on lysimeter under the A_2 horizon at a depth of 42 cm.

1929–30				1930–31			
Laboratory number of leaching	Date	Effective precipitation	Leachings	Laboratory number of leaching	Date	Effective precipitation	Leachings
	1929	*inches*	*liters*		*1930*	*inches*	*liters*
1	June 22	1.71	0.165	25	Dec. 30	1.62	1.870
5	Sept. 9	4.07	2.400		*1931*		
7	Oct. 3	2.10	0.210	26	Feb. 19	1.95	1.200
11	Dec. 20	1.35	0.090	27	Mar. 9	1.09	0.250
	1930			28	Mar. 30	1.60	0.910
12	Feb. 18	1.70	1.265	34	June 18	1.34	0.045
15	June 11	2.45	1.395	..	.....	....	.....
Total for year.....		13.38	5.525	..	.....	7.60	4.275

precipitation to leachings are 2.42 in 1929–30 and 1.77 in 1930–31. It is of interest to note that during the 2 years the ratio of effective precipita-

tion to leachings is about twice as high in A_1 as in A_2 (2.42 and 1.07 for 1929–30 and 1.77 and 0.849 for 1930–31 respectively). *The importance of this ratio constant will be of greater significance if it should reoccur in the succeeding years.* Nothing can therefore be inferred at present from this interesting regularity.

B and C horizons

The function of the B horizon in the soil profile is to "filter" out the substances which move from the overlying A horizon. This is especially true for the soils of the podzol zone, as shown elsewhere (8). Because of that the accumulative nature of the B horizon, known as the horizon of illuviation, is very definitely expressed in this type of soil. Ortstein, orterde, or the so-called various types of hardpan are encountered in the B horizon of these soils. One

TABLE 4

Precipitation and leaching data on lysimeter under B_1 at a depth of 58 cm.

1929–30				1930–31			
Laboratory number of leaching	Date	Effective precipitation	Leachings	Laboratory number of leaching	Date	Effective precipitation	Leachings
	1929	*inches*	*liters*		*1930*	*inches*	*liters*
5	Sept. 9	4.07	0.050	25	Dec. 30	1.62	0.160
	1930				*1931*		
15	June 11	2.45	0.050	26	Feb. 19	1.95	0.050
..	.....	....	.....	28	Mar. 30	1.60	0.025
..	.....	....	.....	33	June 11	1.35	0.040
..	.....	....	.....	34	June 18	1.34	0.020
Total for year.....		6.52	0.100	..	.....	7.86	0.295

of the outstanding properties of this horizon is its relative imperviousness to water. With the advance in age and consequent maturity of such soils, the B horizon becomes more and more impervious. As a result of that the vertical movement of moisture becomes impeded and horizontal movement along this horizon sets in, a phenomenon to be reckoned with in lysimeter studies. This has been pointed out by Gemmerling (5), Kachinskii (9), Popov (21), and others.

In table 4 the leachings of B_1 are presented. It is to be noted that no leachings appeared through B_2, although there were leachings from horizon C, as shown in table 5, and, what is more striking, twice as much as from B_1. Even if we assume that all of the leachings that went through B_1 followed the vertical direction at the point where the funnel in the C horizon is located, there are still about 300 cc. of leachings unaccounted for. Undoubtedly some of the leachings followed the horizontal direction and penetrated the B horizon along root channels, cracks, burrows of insects, worms, and other animals.

The presence of various kinds of concretions in the B horizon may serve as indirect evidence that some of the leachings follow certain channels. Tube-like concretions along root paths and along the edges of crotovinas and many other types of concretions form in the B horizon, because the leachings from above, in their downward movement, strike these paths—the line of least resistance—and deposit on their way the substances which precipitate from solution. Eventually these paths become filled up giving typical concretions.

Why there were more leachings from B_1 in 1930–31 than in 1929–30 may be explained on the basis of the condition of the colloids, which are quantitatively higher in this horizon than in any other. Observations made during the fall of 1930 have shown the extremely dry condition of this horizon. Not much of the rainfall that penetrated through the A_2 horizon was available for the B horizon. Because of the dry condition the structural units increased in size, and cracks were apparent all through this horizon. The non-capillary

TABLE 5

*Precipitation and leaching data on lysimeter in the C horizon at a depth of 80 cm.**

1930–31

Laboratory number of leaching	Date	Effective precipitation	Leachings
	1930	*inches*	*liters*
25	Dec. 30	1.62	0.355
	1931		
26	Feb. 9	1.95	0.080
33	June 11	1.35	0.075
34	June 18	1.34	0.100
Total for year.....		6.26	0.610

* No leachings appeared during 1929–30.

pore space increased and any water that reached this horizon easily percolated through it. Only after December 30, 1930, did the soil in this horizon become saturated and just then a large amount—comparatively speaking—reached the bottom of it.

During this period more than 50 per cent of the leachings percolated through the funnel in the C horizon. And still no leachings appeared from the funnel under B_2. This is undoubtedly due to the phenomenon already referred to, namely, that the moisture is, under certain conditions, not moving entirely in the vertical direction. Because of that there seems to be no consistent relation between the effective precipitation and leachings in either of the B or C horizons. In 1929–30 the ratio of effective precipitation to leachings for the B horizon is about 65, for 1930–31, about 26, and for C it is—in 1930–31—about 10. One might expect a more consistent relation in the C horizon because it is not subject so much to possible horizontal movement of moisture. Its physical and chemical make-up—more or less constant moisture content,

no alternate drying and wetting, fewer colloids—precludes the possibility of much horizontal movement. Another point to remember is that the moisture content of the soil material in this horizon is lower than that of B and will therefore retain less moisture.

Before anything more definite may be said about the nature of the movement of the moisture through B and C, more data—2 to 3 years—will have to be accumulated.

GENERAL DISCUSSION

From the data and discussion presented, certain generalizations about the movement of moisture through the soil profile may be made. First of all, it is apparent that only a small fraction of the rainfall disappears in the form of ground water. If we take the percolation through C as a criterion and consider it as the moisture that goes to feed the ground waters, we find that no moisture was available for the ground waters in 1929–30 and only about *1 per cent* in 1930–31. We must bear in mind that 2 years' results are not sufficient to warrant definite conclusions, especially since the rainfall was below normal in both of these years—10.0 inches in 1929–30 and 13.12 inches in 1930–31. It remains to be seen what the next few years will show.

The next point to be noted is that ordinarily there is not much, if any, horizontal movement of moisture through the A horizon. This makes it possible to assign quantitative significance to the data on the leachings. Quantitative data on the translocation of the substances in the leachings through the profile are very important, although even the qualitative aspect of the data gives a definite picture as to what is going on in the natural soil, as will be shown in the forthcoming papers of this series.

From the agronomic point of view the data on the amount and depth of penetration through the A horizon are very illuminating. A single example may suffice to illustrate this point.

Crop records from this station[10] show that the yield of corn—taking an average of four varieties—in 1929 and in 1930 was 57.4 and 56.9 bushels an acre respectively. The stover yield, however, was 7,826 pounds in 1929 and 12,157 pounds in 1930. The figures in table 1 show that during July, 1929, only 22.45 per cent of the total precipitation was effective, i.e., it penetrated through A_1, whereas during the same month of 1930 the effective precipitation amounted to 76.22 per cent. And it is during this period—before tassling, from July 10 to August 1—that the corn plant makes its vegetative growth. It is reasonable therefore to ascribe the wide variation in yield of stover to the difference in effective precipitation.

An important point to consider in lysimeter studies is the behavior of gravitational moisture in columns of soil material. It has been shown by Lebedev (10) that a short column of sand or soil material will contain more moisture

[10] The author is indebted to Dr. H. B. Sprague, agronomist of the station, for the crop data furnished.

than a long one at certain points at the bottom of the respective columns. He has also shown that short columns of sand or soil give less leachings than the long ones. This raises the question of the percolation of leachings through the columns of soil represented by the various horizons. Of course the columns have to be in a state of saturation and, as may be judged from the data in tables 1, 3, 4, and 5, there was probably no instance of complete saturation of the entire soil column up to the C horizon. We can well imagine the A_1 horizon becoming saturated, and in this case the objection raised by Lebedev is well taken, even though the amount of excessive moisture retained by a soil under such conditions is rather small, as shown by Lebedev's (10) experiments. We also have to remember that in the Lebedev experiments the soil column is physically homogeneous, which would be true for the filled-in type of lysimeters during the first year. It might also be true for the A_1 horizon. And it will not be true even for the filled-in type of lysimeter where two layers of soil are concerned and less so for the new type of lysimeters where each horizon consists of material of variable physical and chemical composition. In such a case the moisture relationships become more complicated as shown by the ingenious experiments of Lebedev (10). Thus the findings of Lebedev could only partly beapplied in the analysis of the moisture relationships in a profile column.

To be sure, a number of reports about lysimeter leachings do show a higher percolation through the deeper lysimeters than through the shallow ones. Lebedev (10) cites the Rothamsted lysimeters, but the data presented by Miller (16) on these lysimeters clearly show that for the first 22 years the reverse was true, namely, the 20-inch lysimeter gave more leachings than either the 40- or 60-inch lysimeters. Only after this period did the deeper lysimeters begin, for a number of years, to show a higher percolation. On the other hand the case of the Ploti Experiment Station lysimeters, as quoted by Lebedev (10), show distinctly that the deep lysimeters have percolated more leachings than the shallow ones. The same is true for the lysimeters at the New York State Experiment Station (1).

It is of interest to note that the new type of lysimeters at the Moscow Regional Experiment Station, as reported by Gemmerling (5), also show the tendency to give larger amounts of leachings from the deeper horizons. This is, however, attributed by Gemmerling to the horizontal movement of the moisture along the B horizon from the adjoining more elevated landscape. In our own case the lysimeters are located on a level plot and there is no chance for moisture from the adjoining area to enrich the supply of the lysimeter plot.

One of the serious objections raised against the inclosed type of lysimeters—and this applies to the filled-in type as well as to the built-in type, the Rothamsted type—is that the soil column is completely shut off from the surrounding soil. There can be percolation downward, but no diffusion of water vapor either from below or the sides, no capillary movement from below or the adjacent soil. In the new type of lysimeters this difficulty has been partly overcome. There is practically no interference for diffusion of vapor or capillary

movement, since the funnel is surrounded with soil and we may consider this obstruction as that produced by a shallow stone in the soil. There is this possibility: because of the pebbles in the funnel the moisture content of the soil just above will have a slightly higher moisture capacity, as shown by Lebedev (10). This, of course, might slightly alter the percolation. In general, however, this new type of lysimeter offers an excellent opportunity to study the movement of moisture through the soil profile and incidentally the translocation of the soil constituents in true and colloidal solution.

SUMMARY

The scope of lysimeter work has been briefly discussed and a critical analysis of the filled-in type of lysimeter presented.

It has been brought out that the lysimeter work at the Cornell, Geneva, Tennessee, and other stations does not represent natural soil conditions, and the findings are of little value in interpreting the reactions that take place in the soil profile.

A new type of lysimeter installed at the New Jersey station has been described. This type of lysimeter permits the study of the percolation and movement of moisture through the soil profile.

Data on the leachings for 2 years have been presented.

Through the A_1 horizon more moisture percolated during the second year notwithstanding the lower precipitation during this year as compared with the first year. The amount of effective precipitation—that which produced leachings—depends on the condition of the colloids in the soil. No correlation was found between the total and effective precipitation.

A higher percentage of the total rainfall percolated through the A_2 horizon during the first year with a high rainfall than during the second year with a lower rainfall. Again the condition of the colloids seem to be responsible for the phenomenon observed.

Along the B horizon the moisture seems to move in a horizontal direction. This may be inferred from the data on the leachings from B and C.

The data seem to indicate that on a level plot only a small fraction of the rainfall is lost to the ground waters. This might not be true in the coming years, for during the last 2 years the departure from the normal precipitation amounted to 10 and more inches.

It has been brought out that the effective precipitation might possibly be correlated with crop production.

A discussion has been presented on the possible abnormalities of the movement of moisture through soil columns of the filled-in type of lysimeter and the new type, in the light of the findings of Lebedev (10).

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PLATE 1

VIEWS OF THE LYSIMETER PIT

FIG. 1. A general view of the location of the lysimeter pit
FIG. 2. Interior view of end of pit where entrance is located
FIG. 3. Interior view of end opposite to entrance of pit

FIG. 1

FIG. 2

FIG. 3

SOLUBLE ALUMINUM STUDIES: I. THE CONCENTRATION OF ALUMINUM IN THE DISPLACED SOIL SOLUTION OF NATURALLY ACID SOILS[1]

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The toxic aluminum theory of soil acidity is based on the assumption that soluble aluminum is found in acid soils in sufficiently high concentrations to be injurious to the growth of plants. Much work has been done in an attempt to prove this theory, as may be seen from the extensive reviews of the literature made by Gile (12), McLean and Gilbert (21), Magistad (22), and others. In spite of the great amount of work that has been done, however, the importance of this theory in explaining the injurious action of acid soils on plant growth in still an unsettled problem. Gile (12) and more recently Line (19) and Hardy (13) have shown the weakness of much of the work upon which the theory is based. Although culture solution studies (21) have well established the fact that aluminum, if present in sufficiently high concentrations, is toxic to plant growth, there is insufficient evidence available from which to conclude that the minimum concentrations found toxic in culture solutions are often found in acid soils. Accurate information, therefore, concerning the concentration of soluble aluminum in acid soils and of factors affecting this concentration is one of the first essentials in a proper evaluation of the toxic aluminum theory of soil acidity.

Three different procedures have been used in studying the soluble aluminum content of soils. The early workers (1, 3, 14, 23) studied the water extract of soils for their soluble aluminum content. This did not prove very satisfactory, however, partly because of the difficulty at that time of determining the small concentrations of aluminum present. The second method of attack involved the use of various salt and acid extracts (4, 7, 9, 18, 20). Although of some value, these methods are open to the serious objection that they do not give the amount of aluminum soluble in the soil water.

More recently a third procedure has been used whereby the displaced soil solution is obtained and is studied for its soluble aluminum content. Since plant roots are in intimate contact with this solution and obtain their nutrients from it, obviously this third general procedure is to be greatly preferred to those

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previously used. Moreover, the recent development of a more accurate method for the determination of small amounts of aluminum makes this general method of attack even more useful.

Burgess and Pember (8) displaced the soil solution of soils from some of the fertilizer plots at the Rhode Island Agricultural Experiment Station and obtained as high as 40 p.p.m. of aluminum in the solution of the untreated soil having a pH of 4.5. Other plots of higher pH values had considerably less or no aluminum in solution.

Magistad (22) and one of the writers (26) have also studied the aluminum in the displaced solution of various soils. The latter found considerably lower values than were found by Burgess and Pember. Moreover, the data of these investigators indicate that different acid soils of similar pH values may contain quite different concentrations of aluminum in their displaced solutions. In view of these facts and the fact that relatively few of the soils used by these investigators were naturally acid soils, it seemed desirable to make a more detailed study of the problem.

The objectives of this investigation are as follows:

To determine the aluminum in the displaced soil solution of a large number of naturally acid soils obtained from various states.

To study the effect of various anions and of total salt concentration on the concentration of the aluminum found in different soils at similar pH values.

To study the seasonal variations in the aluminum concentration of the soil solution.

To study the effect of leaching soils on the concentration of aluminum in the displaced solution.

METHODS OF PROCEDURE

Bulk samples of naturally acid field soils were obtained from nine states.[3] A description of these soils is given in table 1. All the samples except soil 533, 537, and 538 were collected in the early spring of 1931. In most cases they were allowed to dry either before or after shipping and the displacement was made after rewetting the soils to the proper moisture content and after allowing them to stand three or four days for the establishment of equilibrium. Soil 554 and the last six soils of table 1 were obtained from the field at approximately the optimum moisture content and were displaced either on the same day or on the following day. This was also true for the soils given in table 3. Other soils used in this study will be described later.

The soil solutions were obtained by the displacement method of Parker (23) as modified by Burd and Martin (5). Successive portions of the displaced solution were tested for conductivity and for pH in order to make sure that there was no leaching effect in obtaining the solution. In many soils the first 50-cc.

[3] The authors wish to express their appreciation to the following men for sending samples of soils from their respective states: Prof. S. D. Conner, Indiana; Dr. J. A. Chucka, Maine; Dr. R. P. Thomas, Maryland; Dr. A. H. Meyer, Louisiana; Dr. D. R. Dodd and Dr. E. E. Barnes, Ohio; Dr. T. E. Odland, Rhode Island; Dr. N. A. Pettinger, Virginia; and Dr. J. A. Bizzell, New York.

TABLE 1
Description of soils

TABLE 1

Description of soils

SOIL NUMBER	SOIL TYPE	STATE	SOIL PROVINCE	FERTILIZER TREATMENT*	VEGETATION	PLANT GROWTH
533	Wheeling fine sandy loam	W. Va.	River Flood Plains	Light	General crops	Poor
537	Newton fine sandy loam	Ind.	Glacial Lake	None	Natural prairie	Poor
538	Clermont silt loam	Ind.	Glacial and Loessial	None	Timothy	Poor
544	Caribou loam	Maine	Glacial and Loessial	Heavy	Potatoes	Good
546	Elkton silt loam	Md.	Coastal Plains	None	Native grasses and shrubs	Poor
547	Keyport loam	Md.	Coastal Plains	None	Native grasses and shrubs	Poor
548	Portsmouth loam	Md.	Coastal Plains	None	Native grasses and shrubs	Poor
551	Leonardtown silt loam	Md.	Coastal Plains	None	General crops	Poor
554	Dekalb loam	W. Va.	Appalachian	None	Native grass	Poor
561	Monongahela fine sandy loam	W. Va.	River Flood Plains	Light	Pasture	Poor
562	Peat	La.	Coastal Plains	.....	.....	.....
567	Canfield silt loam	Ohio	Glacial and Loessial	Medium	General crops	Good
569	Brooke silt loam	W. Va.	Limestone	None	Meadow	Fair
570	Miami silt loam	R. I.	Glacial and Loessial	Heavy	Shrubs	Fair
571	Miami silt loam	R. I.	Glacial and Loessial	Heavy	Vegetables	Poor
572	Miami silt loam	R. I.	Glacial and Loessial	None	R. I. Bent Grass	Fair
573	Bladen very fine sandy loam	Va.	Coastal Plains	None	Cut-over timber	Fair
574	Lenore fine sandy loam	Va.	Coastal Plains	None	Cut-over timber	Fair
575	Onslow silt loam	Va.	Coastal Plains	None	Cut-over timber	Fair
576	Dunkirk silty clay loam	N. Y.	Glacial Lake	None	General crops	Poor
580†	Canfield silt loam	Ohio	Glacial and Loessial	.....	General crops	Poor
583	Dekalb silt loam	W. Va.	Appalachian	None	Weeds only	Very poor
584	Dekalb silt loam	W. Va.	Appalachian	None	Weeds only	Very poor
586†	Huntington silt loam	W. Va.	River Flood Plains	None	Weeds only	Very poor
587	Holston silt loam	W. Va.	River Flood Plains	None	Native grass	Poor
588	Dekalb silt loam	W. Va.	Appalachian	Medium	Corn	Fair
589	Elk silt loam	W. Va.	River Flood Plains	None	Native grass	Poor
590	Elk fine sandy loam	W. Va.	River Flood Plains	None	Native grass	Poor
591	Westmoreland silt loam	W. Va.	Appalachian	None	Native grass	Fair
592	Dekalb silt loam	W. Va.	Appalachian	None	Native grass	Poor

* Refers to general fertilizer treatment during last 10 years.

† Soils 580 and 586 are poorly drained.

portion going through had a slightly higher pH value than succeeding portions; where the difference was more than one-tenth of a pH this first portion was usually discarded. About 200 cc. of soil solution was usually collected for analysis. Determinations of pH on the soil solution were made by means of the quinhydrone electrode, whereas the determinations on the 1:5 soil-water extract were made by the dialysis-colorimetric method (27). Nitrates were determined in the soil solution by the phenoldisulfonic acid method; chlorides, by titrating with silver nitrate, using potassium chromate as an indicator; sulfates, by the benzidene sulfate method (15); and inorganic phosphates, by the blue colorimetric method as modified by Parker and Fudge (25).

Aluminum was determined by a slight modification of the "aluminum" method described by Winter, Thrun, and Bird (29). Iron and aluminum were first precipitated as the phosphates at pH 4.8 to 5.0. The precipitate was then dissolved in 5 *N* nitric acid and the iron separated from the aluminum by precipitating with 5 *N* NaOH. Centrifuging was used instead of filtering in separating and washing the precipitates. After adding the "aluminon" reagent the solutions were kept at room temperature instead of at 80°C. A series of aluminum standards was prepared at the same time as each set of unknowns, and the colors compared at the end of 20 minutes. With each set of determinations a blank was run on the reagents and corrections were made for it.

RESULTS OF INVESTIGATION

Concentration of aluminum and other ions in the displaced soil solution

The data obtained from a study of the soil solutions of the 30 naturally acid soils from different states are given in table 2. It will first be noted that the pH of the soil extracts varies from 4.0 to 5.0, whereas that of the displaced solutions varies from 3.91 to 4.95. In most cases the soil solution is found to be more acid than the extract, although the difference is unusually slight.

The aluminum concentrations in the displaced solution range from 27.25 p.p.m. for soil 584, which has a pH of 3.91, to a trace for soils 576 and 587, which have pH values of 4.75 and 4.95 respectively. In general, the soils of lower pH contain more aluminum in solution than those of higher pH. However, it is readily evident from an examination of the data that the hydrogen-ion concentration is not the only factor determining the concentration of aluminum in the displaced solution. This is well shown in figure 1. At approximately the same pH values, soils 533, 538, and 571, for example, have from 11.8 to 15.8 p.p.m. of aluminum in solution, whereas soil 572 has only 2.25 p.p.m. Moreover, soils 548 and 573, of considerably higher degree of acidity have only about one-third to one-half as high a concentration of aluminum as soils 533, 538, and 571. Soils 544 and 586 likewise have much higher concentrations of aluminum than other soils of similar or even considerably higher degrees of acidity. These differences in the soluble aluminum concentration of different soils of similar pH values are in agreement with some previous results of one of the writers (26).

The specific resistance of the solutions obtained from the different soils varies considerably. It will be noted from a study of these data that the salt concentration of the solutions, as measured by their specific resistance, influences markedly the concentrations of aluminum at a given pH. The five soils

TABLE 2

Aluminum concentration in the displaced soil solution as affected by H-ion concentration and the concentration of various anions

SOIL NUMBER	SOIL MOISTURE AT DISPLACEMENT (DRY BASIS)	H-ION CONCENTRATION		Al	SPECIFIC RESISTANCE (25°C.)	NO_3	Cl	SO_4	INORGANIC PO_4
		Extract	Soil solution						
	per cent	*pH*	*pH*	*p.p.m.*	*ohms*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*
533	12.8	4.58	4.40	15.80	243	200.0	315	77	N. D.*
537	16.2	4.70	4.60	0.50	593	36.0	200	152	Trace
538	17.4	4.45	4.45	11.80	190	57.8	1,320	20	N. D.
544	24.0	4.95	4.87	1.96	281	122.5	335	868	0.48
546	....	4.80	4.60	0.54	2,584	6.8	58	Trace	0.22
547	13.7	4.70	4.80	1.03	2,281	2.0	82	25	N. D.
548	20.9	4.23	4.25	3.88	1,459	Trace	54	238	N. D.
551	23.2	5.00	4.70	2.38	972	61.3	87	15	N. D.
554	17.0	4.53	4.60	3.05	1,901	21.5	25	81	Trace
561	11.6	4.83	4.60	1.31	1,122	57.5	70	Trace	0.22
562	63.0	4.28	4.21	1.00	457	192.3	60	180	0.60
567	19.7	4.40	4.16	5.75	495	212.5	66	Trace	Trace
569	16.4	4.50	4.34	5.50	261	34.7	1,045	149	0.16
570	17.7	5.00	4.70	1.69	548	56.3	223	149	Trace
571	19.6	4.50	4.45	12.25	148	387.5	216	2,067	0.48
572	15.5	4.53	4.43	2.25	1,133	38.8	128	Trace	0.20
573	22.4	4.35	4.07	5.15	1,579	2.2	126	Trace	0.88
574	....	4.35	4.04	11.82	974	6.2	222	Trace	0.20
575	18.8	4.25	4.00	1.50	399	28.0	495	115	0.09
576	19.8	4.88	4.75	Trace	1,168	46.0	120	Trace	0.35
580	25.2	4.03	4.05	11.63	844	100.2	52	29	0.20
583	22.2	4.00	3.98	22.63	862	14.9	168	155	0.14
584	20.6	4.00	3.91	27.25	898	13.9	149	154	0.28
586	27.8	4.20	4.00	27.20	486	40.0	58	894	Trace
587	19.8	4.85	4.95	Trace	2,268	9.7	90	Trace	0.19
588	17.1	4.60	4.52	3.25	486	50.3	396	21	0.34
589	....	4.95	4.94	0.41	1,032	15.1	206	Trace	Trace
590	19.6	4.60	4.51	0.56	3,429	2.7	48	Trace	0.18
591	26.2	4.68	4.64	0.40	1,714	2.7	126	Trace	0.20
592	24.0	4.45	4.55	0.88	2,209	Trace	37	Trace	0.50

* N. D. means not determined.

previously discussed which were found to have relatively high concentrations of aluminum at their respective pH values are found to be very low in specific resistance or very high in salt concentration. This is readily seen from figure 1. On the other hand, the solutions from soils 546, 547, 587, 590, and 592 which

have the highest specific resistance or lowest salt concentration are relatively very low in soluble aluminum at their respective pH values.

The effect of soluble salts on the concentration of aluminum at any pH value is further illustrated by a comparison of soils 570, 571, and 572. These soils were obtained from the fertilizer plots of the Rhode Island Agricultural Experiment Station (8). Sample 570 was taken from plot 23, which has received a complete fertilizer, including ammonium sulfate plus lime; sample 571, from plot 82, which has received muriate of potash and superphosphate; and sample 572, from the check or untreated plot of the same experiment. It will be noted that samples 571 and 572 have approximately the same pH. The high concentration of salts, however, which had accumulated in sample 571 as a result of poor plant growth and of continued fertilization and consequent

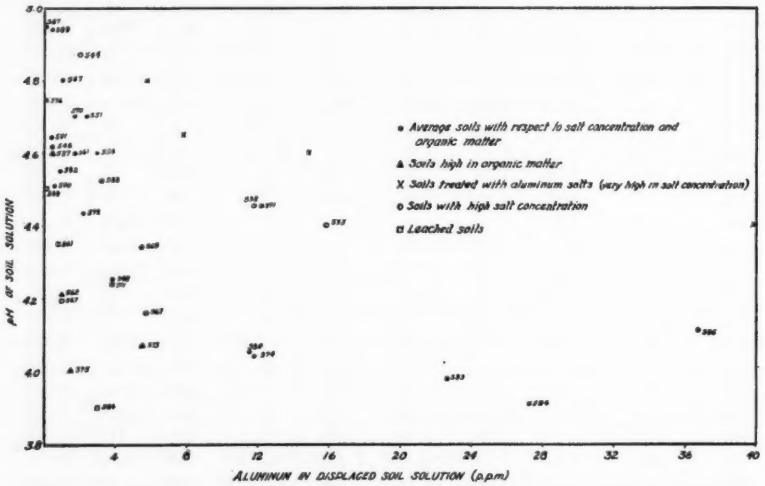
pH OF SOIL SOLUTION
ALUMINUM IN DISPLACED SOIL SOLUTION (p.p.m.)
Average soils with respect to salt concentration and organic matter
Soils high in organic matter
Soils treated with aluminum salts (very high in salt concentration)
Soils with high salt concentration
Leached soils

FIG. 1. EFFECT OF pH ON CONCENTRATION OF ALUMINUM IN DISPLACED SOIL SOLUTION

nitrification has apparently been instrumental in bringing nearly six times as much aluminum in solution as in the untreated soil sample 572.

As is to be expected, a low specific resistance is associated with a high concentration of the various anions. With reference to the five soils previously mentioned which have high concentrations of salts, sulfates are especially high in 544, 571, and 586, whereas chlorides are the most abundant anions in 538 and 533. Nitrates are also abundant, especially in soils 533 and 571. This indicates that all three of these anions are instrumental in bringing aluminum into solution or in determining the concentration of aluminum present at any pH value. The phosphate concentration in the soil solution is very low, and it does not seem to have much influence in determining the amount of aluminum in solution. As will be seen later, however, large amounts of phosphate may

reduce the solubility of aluminum. Therefore, with soils which receive large amounts of phosphate fertilizer and possibly those which have relatively low concentrations of the stronger anions, the phosphate anion may have a marked effect in reducing the concentration of aluminum in the soil solution.

Three soils, 537, 562, and 575, have particularly low concentrations of aluminum when their pH values and salt concentrations are considered. It is significant, however, that all three of these soils are very high in organic matter. This is especially true of soil 562, which is a peat from Louisiana. The only other soil in this group of relatively high organic matter content is soil 573.

It should be noted that soil 554 and the last six soils of table 2, which were displaced immediately after removal from the field, have, in general, a relatively low salt concentration and a low concentration of aluminum as compared with other soils of similar pH. The only exception is soil 588, which, unlike the other six, was under cultivation. This brings out two points that should be emphasized. In the first place, some of the soils which could not be displaced immediately after removal from the field but which were allowed to dry and later moistened for displacement are probably higher in salt concentration and in their content of soluble aluminum than they were when removed from the field. This would be especially true of soils 533 and 537, which had been kept in the greenhouse for some time before displacement. Secondly, since it is known that the hydrogen-ion concentration and soluble salt content of soils may vary with cropping and with the season, it may be expected that the concentration of aluminum present in field soils may vary considerably from time to time.

Seasonal variation in the aluminum concentration of the soil solution

In order to study the effect of season on the concentration of aluminum found in field soils, samples of six of the soils described in table 1 were taken at different times during the year. All of these soils except one were in native vegetation or in grass. Samples taken from the grass areas consisted of at least five shovelfuls of soil taken from an area of less than 10 feet square, each successive sample being taken from within 1 foot of the former sample. In all cases except one, the soil solutions were obtained on the same day that the soils were taken from the field, or else on the following day.

The results obtained are given in table 3. It will be noted that samples taken from the same area at different times during the year vary considerably in aluminum concentration. Moreover, it is evident that this variation is closely related to changes in pH and to changes in the salt concentration of the displaced solution. Soil 554 had about 2½ times as much aluminum in solution curing the middle of the summer, when its hydrogen-ion and salt concentrations were highest, as it did in January or in the following October.

Sample BA of soil 554 was similar to sample B except that it was allowed to remain at optimum moisture content in the soil sample room for nearly two months before being displaced. As a result of bacterial action and a lack of

leaching there were a decided increase in soluble salts and in acidity, and consequently, a nearly threefold increase in the aluminum concentration of the soil solution.

In table 4 are given additional data on the seasonal variation in the aluminum concentration of three small plots of the same soil which had been acidified

TABLE 3

Aluminum concentration in the soil solution of naturally acid field soils at different times during the year

Soil		Date of sampling	Sample number	H_2O	H-ion concentration		Al in soil solution	Specific resistance (25°C.)	NO_3 nitrogen in soil solution	PO_4 in soil solution
Number	Type				Soil extract	Soil solution				
				per cent	*pH*	*pH*	*p.p.m.*	*ohms*	*p.p.m.*	*p.p.m.*
554	Dekalb loam	January	A	17.0	4.53	4.60	3.05	1,901	21.5	N. D.
		May 21	B	16.5	4.35	4.39	4.75	2,209	22.4	0.06
		July 10	BA*	....	....	4.15	12.00	794	115.0	Trace
		July 10	C	14.8	4.40	4.15	7.75	891	38.0	Trace
		October 17	D	15.2	4.60	4.47	3.20	1,872	Trace	N. D.
587	Holston silt loam	May 21	A	19.8	4.85	4.95	0	2,268	9.7	0.15
		July 10	B	22.8	4.40	4.40	0.88	3,741	Trace	0.11
		October 17	C	22.3	4.93	4.77	0	2,072	None	N. D.
588	Dekalb silt loam	May 21	A	17.1	4.60	4.52	3.25	486	50.3	0.34
		July 10	B	15.5	4.93	4.60	1.88	367	176.0	0.34
		October 17	C	15.4	5.03	5.05	0	1,253	40.4	N. D.
590	Elk fine sandy loam	May 21	A	19.6	4.60	4.51	0.56	3,429	2.7	0.18
		July 10	B	18.1	4.60	4.45	1.25	1,198	31.0	Trace
		October 17	C	17.0	4.75	4.66	0	4,324	None	N. D.
591	Westmoreland silt loam	May 21	A	26.2	4.68	4.64	0.40	1,714	2.7	0.20
		July 10	B	21.0	4.60	4.35	1.22	880	Trace	0.07
592	Dekalb silt loam	May 21	A	24.0	4.45	4.45	0.88	2,209	Trace	0.50
		July 10	B	23.2	4.85	N. D.	0.28	648	Trace	0.07
		October 17	C	26.8	4.90	4.86	0	2,026	Trace	N. D.

* Sample BA is the same as B except that it was kept moist for nearly 2 months before displacement.

with sulfuric acid. Since the sulfuric acid had been added nearly 3 years previously and since two crops had previously been removed from these plots, the soils were probably at much the same kind of equilibrium as if they had become acid naturally. The data further illustrate the fact that changes in pH and in salt concentration which may result from cropping, leaching, and from seasonal

variation in the biological activities in the soils (28), influence very markedly the soluble aluminum content at different times during the year.

Effect of leaching on the concentration of soluble aluminum in soils

The effect of leaching on the soluble aluminum content of soil solutions was studied with five soils used in the former studies. These soils vary in the aluminum concentration of their solutions from 1.31 to 27.25 p.p.m. Fourteen kilograms of each soil were placed in pots and leached with 16 liters of distilled water. The soils were then allowed to dry for about a week, at the end of which time they had reached a moisture content optimum for displacing the solution.

The data on the analyses of the solutions are given in table 5. It will be seen that leaching the soils reduced very markedly the aluminum concentration of the soil solutions. The greatest changes occurred with soil 569, where the

TABLE 4

Aluminum concentration in the displaced solution of artificially acidified soils at different dates

PLOT	DATE OF SAMPLING 1931	CROPPING DATA	H-ION CONCENTRATION		SPECIFIC RESISTANCE (25°C.)	Al	NO_3
			Soil extract	Soil solution			
			pH	*pH*	*ohms*	*p.p.m.*	*p.p.m.*
Barley A	April 7	Barley seeded April 10, harvested July 4, 1931	4.25	4.40	425	2.00	56
	June 15		4.20	4.00	625	2.63	133
	July 6		4.25	4.05	489	5.25	115
Rye A	June 29	Rye seeded October 2, 1930; harvested June 24, 1931	4.20	4.00	400	9.25	15
	October 3		4.40	4.20	298	14.70	109
Rye B	June 29		4.58	4.45	681	0.58	38
	October 3		4.60	4.35	256	4.50	80

reduction was from 5.50 p.p.m. to a trace and with soil 584, where the concentration of 27.25 p.p.m. was reduced to 3.00 p.p.m. Although in two cases this decrease might be partly explained by a slight decrease in acidity, the main reason is evidently the marked decrease in the salt concentration as is shown by the data on specific resistance and by those on the concentration of the various anions. The slight increase in salt concentration as measured by the specific resistance and in chlorides in soil 561 may probably be explained by the fact that the soils were allowed to remain moist for several weeks between the time of the first displacement and leaching. The concentrations of total salts and of aluminum just prior to leaching were, therefore, probably higher than is shown in the table.

Effect of different anions in bringing aluminum into solution

Since the investigations of Joffe and McLean (16, 17) show that aluminum is soluble at higher pH values as the chloride or nitrate than as the sulfate, it

seemed of interest to compare the effect of additions of aluminum sulfate, aluminum nitrate, aluminum chloride, and phosphoric acid on the concentra-

TABLE 5

Effect of leaching soils on the aluminum concentration in the displaced solution

SOIL NUMBER	LEACHING TREATMENT	H-ION CONCENTRATION		Al	SPECIFIC RESISTANCE (25°C.)	NO_3	Cl	SO_4	PO_4
		Soil extract	Soil solution						
		pH	*pH*	*p.p.m.*	*ohms*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*
561	None	4.83	4.60	1.31	1,122	58	70	Trace	0.22
	Leached	4.97	4.35	0.81	1,010	31	156	Trace	0.06
567	None	4.40	4.16	5.75	495	213	66	Trace	Trace
	Leached	4.65	4.20	0.88	1,134	65	64	Trace	Trace
569	None	4.50	4.34	5.50	261	35	1,045	149	0.16
	Leached	5.02	4.50	Trace	1,344	16	112	Trace	0.15
571	None	4.50	4.45	12.25	148	388	216	2,067	0.48
	Leached	4.37	4.25	3.83	671	39	64	344	0.17
584	None	4.00	3.91	27.25	898	14	149	154	0.28
	Leached	4.25	3.90	3.00	1,768	12	76	Trace	0.06

TABLE 6

The concentration of aluminum and other ions in the displaced solution of a soil treated with various aluminum salts or with phosphoric acid

POT NUMBER	TREATMENTS		H-ION CONCENTRATION		Al	SPECIFIC RESISTANCE (25°C.)	NO_3	Cl	SO_4
	Kind of solution	Amount of solution*	Extract	Soil solution					
		cc.	*pH*	*pH*	*p.p.m.*	*ohms*	*p.p.m.*	*p.p.m.*	*p.p.m.*
1–2	None	...	5.40	5.80	0.5	280	320	126	180
3–4	$Al_2(SO_4)_3$	120	4.53	4.60	14.9	207	240	93	1,989
5–6	$Al_2(SO_4)_3$	224	4.30	4.35	58.5	199	104	66	2,808
7–8	$Al_2(SO_4)_3$	344	4.05	4.20	272.0	108	400	261	4,113
9–10	$Al(NO_3)_3$	120	4.70	4.80	5.8	143	850	118	246
11–12	$Al(NO_3)_3$	224	4.43	4.40	40.2	98	1,350	68	Trace
13–14	$Al(NO_3)_3$	344	4.00	4.00	665.0	47	3,150	118	Trace
15–16	$AlCl_3$	120	4.63	4.65	7.8	103	330	2,420	137
17–18	$AlCl_3$	224	4.38	4.35	63.5	72	150	4,740	106
19–20	$AlCl_3$	344	4.00	4.20	296.4	54	120	6,685	120
21–22	H_3PO_4	240	4.78	4.90	1.2	191	440	175	442
23–24	H_3PO_4	688	4.68	4.60	0.4	285	280	102	397

* Refers to cc. of *N* solutions per 8,000 gm. of soil.

tion of aluminum in the displaced soil solution. Three different amounts of each of these salts and of phosphoric acid were added to duplicate pots of a

Wheeling fine sandy loam. These pots were kept at optimum moisture content at the greenhouse for about 4 months before their displaced soil solution was obtained. The analyses of the solutions are given in table 6. As was to be expected, the additions of the aluminum salts decidedly increased the acidity of the soil. The increase in acidity alone, however, does not explain the extremely high concentrations of soluble aluminum obtained. It will be readily noted from figure 1 that the concentration of aluminum in the soils treated with the different aluminum salts is much higher at given pH values than for normal acid field soils. The high values are no doubt primarily due to the high salt concentration which resulted from the addition of aluminum salts and possibly also from bacterial action during the incubation period.

No differences in the direct effect of the different anions, chlorides, nitrates, and sulfates on the aluminum concentration were obtained. This is best seen by plotting the pH values of the solution against their concentration of aluminum. Some of the points are shown in figure 1, and it will be noted that they form a rather smooth curve. Apparently the differences in soluble aluminum obtained from the addition of equivalent amounts of these salts are due to slight differences in the pH of the solutions. This substantiates some of the results obtained from the study of the miscellaneous soils, namely, that high concentrations of any one of these three anions in the soil result in a high concentration of soluble aluminum in the displaced solution. This would seem to be in contradiction to the work of Joffe and McLean (16), who found that aluminum sulfate was less soluble in water solutions at certain pH values than aluminum chloride and nitrate. It must be remembered, however, that these investigators worked with pure solutions. It is possible that under other conditions in soils, as might be obtained at higher pH values or when only one kind of anion is present, differences might be found in the aluminum concentration at similar pH values, dependent on whether the anions are sulfates, nitrates, or chlorides.

On the other hand it will be noted from table 6 that the addition of large amounts of phosphoric acid increased the hydrogen-ion concentration of the soil without greatly changing the aluminum in solution. This is what would be expected since aluminum phosphate is readily precipitated except at very low pH values (13, 19).

Statistical analysis of aluminum content, hydrogen-ion concentration, and specific resistance[4]

It is obvious from the data presented that some interrelation exists among the aluminum content, hydrogen-ion concentration, and specific resistance of the displaced soil solution. In order to determine more precisely the magnitude of this interrelation, correlation studies were made of the data presented in table 2. For this statistical study soils 537, 562, 573, and 575 were omitted

[4] The statistical analysis was suggested by Dr. R. J. Garber, head of the department of agronomy and genetics.

because, as has already been explained, they are high in organic matter and are not typical mineral soils. In all calculations the acidity of the soil solution was expressed as hydrogen-ion concentration rather than pH.

The simple linear correlation between aluminum content and specific resistance was found to be -0.422, after making the usual correction for the small number making up the sample ($n = 26$). This correlation is not high but it has some significance. According to Fisher's tables (11) the P value is slightly less than 0.05. The chance of obtaining as good or better correlation from uncorrelated data is therefore approximately 1 to 19. With a correlation coefficient (r) of -0.422 the coefficient of determination (r^2) becomes 0.178. In terms of aluminum content and specific resistance this means that approximately 18 per cent of the variance in aluminum content is associated with that in the specific resistance of the displaced soil solution.

In a similar manner, the linear correlation between aluminum and hydrogen-ion concentration was found to be $+0.584$, which is highly significant and indicates a marked relationship. The coefficient of determination (r^2) in this case is 0.729. In other words, approximately 73 per cent of the variance in aluminum content may be accounted for by the variance in hydrogen-ion concentration.

Since simple linear methods show a significant correlation in both of the relationships it seemed desirable to use multiple correlation methods to determine the combined effects of the two independent variables (specific resistance and hydrogen-ion concentration) on the dependent variable (aluminum). These give a coefficient of total correlation (R) of 0.877. The corresponding coefficient of total determination is therefore 0.770, showing that 77 per cent of the variance in aluminum concentration is explained by the combined linear effects of hydrogen-ion concentration and specific resistance. This value is slightly higher than the simple correlation between aluminum and hydrogen-ion concentration. It is apparent that by taking into consideration specific resistance, 14.9 per cent of the variance in aluminum concentration left unexplained by hydrogen-ion concentration has been accounted for. This means that there is a partial correlation coefficient between aluminum and specific resistance of 0.386. The partial correlation coefficient between aluminum and hydrogen-ion concentration is 0.849.

While making these linear analyses certain graphs were prepared which gave an indication that the relationships could best be explained by curvilinear correlation. The short-cut method as given by Ezekiel (10) was used for this analysis. When applied to the data this method gives a corrected P value (index of total correlation) of 0.939 and a P^2 (index of total determination) of 0.881, which shows that about 88 per cent of the variance in aluminum can be explained by a curvilinear relationship with hydrogen-ion concentration and specific resistance. This value as compared to 0.770 for coefficient of total determination shows that the variance explainable by the use of curvilinear relationships is considerably greater than that by the use of linear relationships.

The analyses show very clearly that the aluminum content of the displaced soil solution is very closely associated with hydrogen-ion concentration and specific resistance and that these two variables are of primary importance in explaining variations in the aluminum present in the soil solution.

GENERAL DISCUSSION

The data presented in this paper establish the fact that there is not just one solubility curve for aluminum in the soil solution at different pH values. This is contrary to the conclusions of Magistad (22). This author in a very comprehensive investigation of the subject of the toxic aluminum theory determined the solubility of aluminum sulfate in water at different pH values, and also the solubility of aluminum in displaced soil solutions of different reactions. He concluded that "since the two curves practically coincide, one can predict with a fair degree of certainty the amount of soluble aluminum present in a soil solution on knowing the pH of the soil." The explanation of Magistad's results probably lies in the fact that he obtained most of his data from soils treated with different amounts of acid. The soil solutions were, therefore, probably all high in total salt concentration. In the present investigation it has been shown that the salt concentration of the displaced soil solutions materially affects their concentration of aluminum.

The indication that organic soils or soils high in organic matter have low concentrations of aluminum in solution even when very acid is in accord with the observations of Burgess and Pember (8), that "large amounts of decomposing organic matter are efficient in counteracting the deleterious effects of active aluminum upon sensitive crops." It may also help to explain why good crops are sometimes grown on very acid peat soils containing plenty of calcium (2) since these soils are probably also low in soluble aluminum.

Another factor which may possibly affect the concentration of aluminum in the soil solution at any pH value is the percentage base saturation of soils. Other things being equal, soils of relatively high percentage base saturation at low pH values might be expected to have relatively less aluminum in solution than others of low percentage base saturation. Some indication of this was found in a previous investigation (26).

The concentration of aluminum in the displaced soil solution was found to vary greatly from time to time during the season. Not only was this found to be associated with changes in pH but also with changes in the soluble salt content of the soils. Any factor that influences either or both of these properties of an acid soil will, therefore, influence the concentration of soluble aluminum present. Among such factors may be listed the following: presence or absence of a crop, kind of crop grown, biological activities in the soil, weather conditions as they may affect biological activities and leaching of soluble salts, drainage, addition of fertilizers, moisture content of soils.

Examples of the operations of these factors can readily be found in the data presented. Relatively high concentrations of aluminum were found associated

with: (*a*) the absence of a crop, and the action of biological agents, such as in samples "Rye A" and "Rye B" of table 4, and in soils 533 and 538; (*b*) the absence of good drainage, as in soils 580 and 586; (*c*) and the addition of soluble fertilizer salts, as in soil 571. On the other hand, relatively low concentrations of aluminum were found associated in these acid soils with the presence of a growing crop, as in the last four soils of table 2 and in the "Barley A" soil of table 5, and with leaching, as shown by the results given in table 4.

That soils vary considerably in the salt concentration of their displaced solution has also been shown by Burd and Martin (6). They not only found seasonal variations in the soil solution, but they showed that there is an inverse relation between the concentration of total salts—and of certain very soluble ions such as chlorides and nitrates—in the soil solution and the moisture content of the soil. Therefore, in a period of little rainfall, the amount of moisture in the soil may be so reduced as to increase very materially the soluble salt content and thereby the concentration of aluminum in the soil solution. On the other hand, heavy rains accompanied by leaching will decrease the soluble aluminum concentration.

In considering the data presented, it must be remembered that these soils are very acid. Nevertheless, large areas of such soils are found in the northern humid sections of the United States. They represent many different soil types and with one exception are naturally acid soils. A few of the soils which had a very high concentration of aluminum, however, are not truly representative of the average acid soil under field conditions, for they contained a very high concentration of salts.

It is evident from these data that it is difficult to assign definite values for the amount of aluminum in soil solutions at certain pH values. In general, however, it may be concluded that the displaced solution of soils of pH 4.5 or above probably rarely contains under field conditions more than 5 p.p.m. of aluminum, soils of pH 4.8 seldom more than 2 p.p.m., and soils of pH 5.0 seldom more than 1 p.p.m. of aluminum. In the presence of a crop and where frequent rains keep the soluble salt content of the soil very low, the concentration of aluminum in the displaced soil solution may be less than 1 p.p.m. at pH 4.5 and zero at pH 4.8 or above.

These data are believed to be important in determining the validity of the toxic aluminum theory of soil acidity. Not only do they help to explain certain conflicting results regarding the soluble aluminum concentration of acid soils, but they should help in interpreting some of the results of culture solution work and in determining the importance of soluble aluminum as a factor in explaining poor plant growth on acid soils. A more detailed consideration of these relationships will be given in some of the subsequent papers of this series.

SUMMARY

Thirty very acid soils representing some principal soil types were obtained from nine states and the relations between their soluble aluminum content and

the concentration of hydrogen and other ions and salts in the displaced soil solution, were studied. The results show that:

The concentrations of aluminum in different soils of similar pH values vary greatly. For example; at pH 4.0, it ranges from 1.5 to about 23 p.p.m.; at pH 4.5, from 0 to about 12 p.p.m.; and at pH 4.9, from 0 to about 2 p.p.m.

The concentration of soluble salts in the soil affects very materially the concentration of aluminum in solution at any given pH value.

The presence of high concentrations of the anions, chlorides, sulfates, and nitrates seem to be equally effective in maintaining a high concentration of aluminum in the soil solution.

Soils having high contents of organic matter contain much less aluminum in solution at given pH values than soils low in organic matter.

A statistical analysis of the data by linear methods showed that 73 per cent of the variance in the aluminum concentration of the soil solution can be accounted for by its relationship to hydrogen-ion concentration. Of the remaining variance, approximately 15 per cent was explained by variation in the specific resistance of the solutions. By using curvilinear methods, it was found that 88 per cent of the variance in aluminum was associated with variations in hydrogen-ion concentration and specific resistance of the soil solutions.

A number of soils in native grass and in general crops were studied at different times of the season for their soluble aluminum content. There was found a marked seasonal variation in the aluminum concentration of the soil solution, and this variation was found to be associated with variations in the soluble salt content.

Leaching soils high in soluble aluminum was found to decrease very greatly the aluminum concentration in the soil solution.

Addition of different amounts of aluminum salts to soil was found to result in a very high concentration of aluminum in the displaced solution.

Attention is called to the various factors which may influence the seasonal variations in the pH and total salt content of soils and consequently the aluminum concentration in the soil solution.

It is emphasized from a consideration of these data that there is not just one solubility curve for the concentration of aluminum in displaced soil solutions at various reactions.

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